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Technical Research in Advanced Air Transportation Technologies

Single-Year, NAS-Wide Benefits Assessment of TFM R&D

Final Report

NASA Technical Monitor:

Daniel Kozarsky

Authors:

Simon Evans

Antony Evans

Husni Idris Ph.D. - Principal Investigator

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Prepared For:
NASA Ames Research Center
Moffett Field, CA 94035-1000

Prepared By:

Titan Corporation
Air Traffic Systems Division
700 Technology Park Drive
Billerica, MA 01821

TITAN SYSTEMS CORPORATION
AIR TRAFFIC SYSTEMS DIVISION

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Executive Summary

The Advanced Air Transportation Technologies (AATT) project of NASA is developing Traffic Flow Management (TFM) research and development (R&D) tools as extensions of the Future Air Traffic Management Concept Evaluation Tool (FACET). FACET provides an environment for modeling, developing, and evaluating improved concepts for system-wide operations over the national airspace prior to operational use. TFM R&D will extend the modeling and simulation capabilities of FACET to provide planning and evaluation tools to enable more efficient National Airspace System (NAS) operations by removing unnecessary restrictions. TFM R&D tools are intended to support the internal and collaborative decision-making processes of the FAA and Airline personnel with regard to traffic flow management. The adaptation of FACET to meet the needs and requirements of the FAA Command Center (ATCSCC) and other FAA facilities is referred to as the System-Wide Evaluation and Planning Tool (SWEPT). The adaptation of FACET to satisfy the needs and requirements of the Airline Operation Center (AOC) is called FACET-AOC. The objective of this task is to provide an initial assessment of the potential NAS-wide benefits of TFM R&D tools for a recent year and for the year 2015.

The overall approach to the study started with the identification of benefit mechanisms according to an analysis of the capacity constraints and TFM procedures in the current NAS and an analysis of the TFM R&D functions. Current TFM procedures were studied through literature review and based on results of NASA's TFM R&D research as described in Section 3 of this report. Traffic flow management procedures attempt to maintain demand below two main NAS constraints: the airport acceptance rates and the airspace sector load capacities. Limitations in the current TFM procedures include the lack of integration between current TFM programs, the lack of collaboration between the FAA and the airlines in responding to TFM constraints, and the lack of the ability to simulate and perform what if type analysis with regard to initiating and selecting TFM programs.

A careful assessment of the tools' functionality was accomplished by analyzing TFM R&D literature and through consultation with NASA's TFM R&D researchers. Because of the early stage of development of TFM R&D tools and the large possibilities for tool extensions, a wide range of functions was identified as described in Section 4 of this report. However, due to time and resource limitations, the benefit assessment had to be focused on a subset of these functions. The list of TFM R&D functions was thus prioritized, and the following functions were identified by NASA TFM R&D researchers to be the most important, and were thus chosen for further analysis:

- SWEPT decision support in rerouting around a Flow Constraint Area (FCA).
- SWEPT decision support in airspace resectorization.
- FACET-AOC decision support in airline collaborative response to NAS congestion, particularly preemptive actions by the airlines.

Benefit mechanisms were then derived by applying each of the TFM R&D main functions to alleviate the identified limitations in the current TFM procedures. In order to achieve clarity, consistency, and reviewability by NASA's TFM R&D researchers, each

function was mapped into quantifiable benefits and the mapping was represented in flow diagrams. The derivation of benefit mechanisms is described in Section 5 of this report. The modeling methodology of each of the three main functions and their benefit mechanisms is also described in Section 5. In order to simplify the analysis, a generic modeling methodology was developed whereby each benefit mechanism can be modeled through a small incremental modification to the overall model.

The approach in this study was to compare the performance of the simulated operations with the use of TFM R&D tools to the performance of simulated baseline operations under current TFM procedures. The simulation tool used was FACET, which is also the basic engine of the TFM R&D tools that are analyzed. FACET's trajectory generation function was used for demand modeling. For capacity modeling the Monitor Alert Parameter (MAP) reported in FACET were used to represent the sector load capacities. Algorithms (such as integrated rerouting and metering) were developed to represent improved TFM procedures with the support of the TFM R&D tools. These algorithms were developed for the main three TFM R&D tool functionalities and according to the benefit mechanisms of these functionalities presented in Section 5. These algorithms were developed using MATLAB and interacted with the FACET simulation through inputs and outputs.

The technical performance benefits of TFM R&D tools, in terms of delay savings, are detailed in Section 6. These technical performance benefits include the benefits of SWEPT decision support in rerouting around a Flow Constraint Area (FCA); SWEPT decision support in solving airspace design and resectorization problems; and FACET-AOC decision support in airline response to NAS congestion, particularly preemptive actions by the airlines. The technical performance benefits are presented for transcontinental playbook reroutes (CAN_1_EAST, VUZ and FAM) on three days (June 11, 2003, September 15, 2002 and August 16, 2002 respectively) affected by severe weather. Technical performance benefits are also presented for airport closure reroutes (IAH_EAST and DFW_EAST) on two days (August 16, 2002 and September 19, 2002 respectively) affected by severe weather.

In Section 7 of the report the technical performance benefits identified in Section 6 are converted into economic terms. This includes average economic savings per reroute type (transcontinental and airport closure playbook reroutes), and an extrapolation to yearly economic savings according to an estimate of the number of transcontinental and airport closure playbook reroutes implemented per year. The yearly benefits of using SWEPT and FACET-AOC under current level of traffic demand are summarized in the table below.

Table 1. Yearly economic benefits of TFM R&D selected functions

Analyzed TFM R&D Functions	Yearly Savings [US$/year]
SWEPT: Improved Rerouting around FCA	$ 84,253,000
SWEPT: Airspace Dynamic Resectorization	$ 14,568,000
FACET-AOC: Preemptive Airline Collaboration	$ 97,077,000

Section 8 presents an extrapolation of the above results to 2015. These yearly benefits of using SWEPT and FACET-AOC in 2015 are summarized in the table below.

Table 2. Yearly economic benefits of TFM R&D selected functions extrapolated to 2015

Analyzed TFM R&D Functions	Yearly Savings in 2015 [US$/year]
SWEPT: Improved Rerouting around FCA	$ 186,953,000
SWEPT: Airspace Dynamic Resectorization	$ 95,561,000
FACET-AOC: Preemptive Airline Collaboration	$ 277,976,000

The benefit estimates reported in this study are believed to be low fidelity and conservative due to a number of reasons:

- This study focused on only a subset, namely three, of the possible TFM R&D functions.
- Only a subset of the benefit mechanisms of these three functions was assessed. The benefit mechanisms that were analyzed included:
  - The use of SWEPT for simulating different playbook reroutes and selecting one reroute based on integrated rerouting and metering – only one example of possible integration between TFM programs. The reroute with least total delays was selected where total delays were caused by reroute distance and metering due to congestion.
  - The use of SWEPT for allocating and distributing flights over more than one reroute, also integrating rerouting and metering in the allocation decision.
  - The use of SWEPT for collaboration with airlines to allocate flights between playbook and customized reroutes.
  - The use of SWEPT for changing sector boundaries to distribute and reduce sector overload and reduce the need for metering.
  - The use of FACET-AOC for one airline or all airlines re-filing of alternate routes for their flights affected by an FCA to reduce the need for FAA metering.
- Only airport closure and transcontinental reroute scenarios were selected to cover the two most prominent playbook reroute types; but no other reroute types nor other TFM restrictions (such as temporal restrictions) were considered.
- This study covered more functions at the expense of more details for each specific function. A number of simplifying assumptions were made, given the wide range of functions covered and the non-constraining fidelity requirements.

This leads to the belief that the benefit estimates reported in this study are conservative and low fidelity, both for TFM R&D in general and for the specific functions analyzed in particular. Therefore, they should be considered only a portion of the possible total benefits of TFM R&D. Future work may focus on each individual function and perform more comprehensive and higher fidelity assessment of its benefits as the Technical Readiness Level (TRL) of the TFM R&D tools increase. This study can serve as a starting point and a preliminary assessment.

1. Introduction

The Advanced Air Transportation Technologies (AATT) project of NASA is developing Traffic Flow Management (TFM) R&D tools as extensions of the Future Air Traffic Management Concept Evaluation Tool (FACET). FACET provides an environment for modeling, developing, and evaluating improved concepts for system-wide operations over the United States airspace prior to operational use. TFM R&D will extend the modeling and simulation capabilities of FACET to provide planning and evaluation tools to enable more efficient National Airspace System (NAS) operations by removing unnecessary restrictions. TFM R&D tools are intended to support the internal and collaborative decision-making processes of the FAA and Airline personnel with regard to traffic flow management. The adaptation of FACET to meet the needs and requirements of the FAA Command Center (ATCSCC) and other FAA facilities is referred to as the System-Wide Evaluation and Planning Tool (SWEPT). The adaptation of FACET to satisfy the needs and requirements of the Airline Operation Center (AOC) is called FACET-AOC.

TFM is a collaborative decision-making process involving the airlines and the FAA. While the FAA is responsible for the overall safety and smooth flow of traffic in the NAS, the airlines are responsible for operating their individual aircraft safely and efficiently such that their schedules are maintained. This difference in emphasis leads to different functional requirements for the development of SWEPT and for the development of FACET-AOC.

The objective of this task is to provide an initial assessment of the potential NAS-wide benefits of TFM R&D tools (including SWEPT and FACET-AOC) for a recent year and for the year 2015. Results from this task will serve multiple functions: (1) to better understand the benefit mechanisms of SWEPT and FACET-AOC such that the tool design may focus on the highest payoff areas, (2) to satisfy the AATT milestone Single-Year Benefits Assessment of TFM R&D in support of the SWEPT TRL 1-3 transition, and (3) to lay the groundwork for the AATT milestone Life-Cycle Cost/Benefit Assessment of TFM R&D, in support of the SWEPT TRL 4-5 transition.

2. Approach and Methodology

Figure 1 illustrates the general approach by which the benefits of TFM R&D are identified and analyzed.

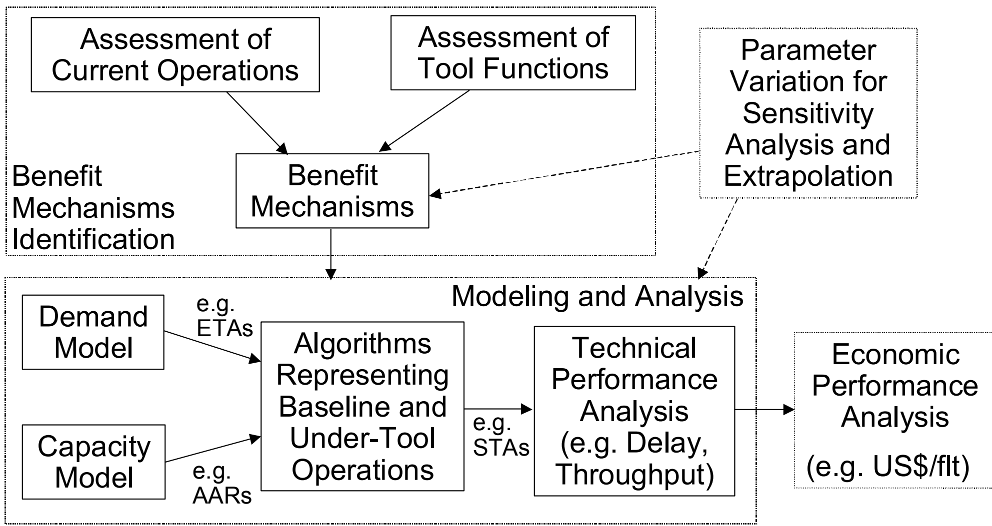

Figure 1. General benefit analysis approach.

2.1. Identification of Benefit Mechanisms

First, the benefit mechanisms of TFM R&D are identified. In order to ensure that as many benefits are captured as possible, the applicability of the benefit mechanisms identified, and feedback from TFM R&D researchers, it is essential that a formal, reviewable approach to the identification of the benefit mechanisms be developed. Therefore, for the purpose of clarity, consistency, and completeness, functions, constraints and benefits are formally defined as follows:

- A *Function* is a user utility of the tool.
- A system *Constraint* is any condition that causes demand to exceed capacity of a NAS resource.
- A *Benefit* is a quantifiable performance advantage or operational enhancement that has a direct stakeholder impact.
- An *Economic Benefit* is a benefit directly quantifiable in monetary terms, and leads directly from a *Benefit*.
- A *Benefit Mechanism* is a linkage that converts a function into a benefit by applying the *function* to alleviate system *Constraints*.

A function excites a benefit mechanism, which creates a benefit. The benefit mechanism may include any number of steps. Based on these definitions, the benefit mechanism identification approach includes the following primary components:

1. Assessment of the current NAS operations and flow management procedures, identifying their constraints and limitations.
2. Assessment of the TFM R&D functionality.
3. Identification of the benefits of each TFM R&D function by applying the function to alleviate the identified system constraints and limitations. This includes mapping separate benefit mechanisms for each function according to the constraints of current operations.

By identifying TFM R&D functionality before the identification of benefit mechanisms it is ensured that benefits from all TFM R&D functions are accounted for. The current constraints, TFM R&D functionality, and TFM R&D benefit mechanisms identified are detailed in Sections 3, 4 and 5, respectively, along with details of the modeling of each.

2.2. Modeling and Baseline Comparison

After identification of the key benefit mechanisms of TFM R&D relative to current operations, the current (baseline) system and that as enhanced by TFM R&D tools are modeled accordingly. This enables the performance of the two systems to be measured and compared. The modeling includes algorithms that represent the NAS operations under TFM R&D tools and the baseline operations. Inputs to these algorithms come from models of the system demand and of the system capacity. The output of the algorithms is then analyzed in order to determine the system technical performance and then economic performance.

In order to measure the performance of the operations with the use of TFM R&D tools, these operations need to be simulated. Algorithms representing TFM procedures (such as rerouting and metering) improved with the support of TFM R&D tools were developed. These algorithms were developed according to the TFM R&D tool functionalities, which were assessed based on feedback from NASA's researchers as represented in Section 4.

The performance of the baseline may be measured with actual traffic data on days when TFM restrictions were imposed according to current procedures. However, the actual traffic data may provide a misleading measurement of the baseline performance for a number of reasons. One reason is that the actual traffic data includes a manifestation of all the sources of inefficiency in the current operations, not all of which may be addressed by TFM R&D tools. Care therefore, must be taken to exclude the non-relevant sources of inefficiency when selecting actual traffic samples for measuring the baseline performance. Failure to do so renders the estimated benefits optimistic. Another reason the actual traffic data may provide a misleading measurement of baseline performance is the discrepancy between the reported information and the actual operation of the system. The actual data reflects the performance of the operations under the imposed restrictions, which often do not match the reported restrictions. (For example, when 15 miles in trail are specified often 13 miles in trail may be imposed in practice, resulting in a higher throughput than expected have 15 miles in trail been imposed.)[1] In such cases the system outperforms, in terms of delay and throughput, the performance expected given the reportedly imposed restrictions. Failure to account for such an inaccuracy renders the estimated benefits conservative and often negative.

The performance of the baseline may also be measured with simulated traffic data under TFM restrictions that are modeled according to current procedures. This approach eliminates the inaccuracy in measuring the baseline using actual traffic data. The simulation would allow concentrating on the elements that are believed to be relevant to the benefits assessment by excluding the sources of inefficiency that may not be mitigated by TFM R&D tools. Examples of such an approach include the benefit study of Regional Metering, a potential enhancement to TMA/McTMA, TO71 [1], which used simulated current operations as a baseline instead of using the actual data. TO71 used for the baseline an algorithm that selects optimal MIT restrictions.

The approach in this study was to compare the performance of the simulated operations with the use of TFM R&D tools to the performance of simulated operations under current procedures as a baseline, as shown in Figure 2.

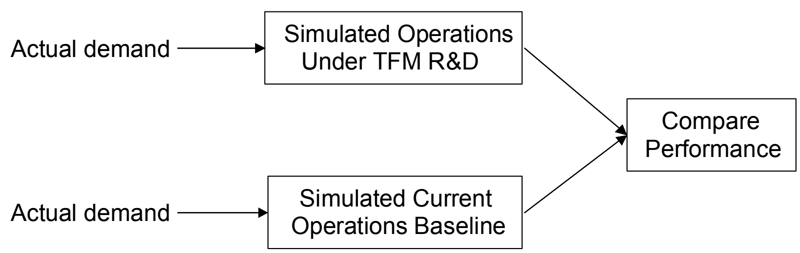

Figure 2. Comparison of TFM R&D and baseline operations

The simulation tool used was FACET, which is also the basis for the TFM R&D tools that are analyzed. The performance of the baseline measured by actual traffic data remains important for the purposes of calibration of the simulated baseline and for the identification of the available pool of inefficiencies in the current operations and the fraction of it that TFM R&D tools may mitigate. Based on feedback from NASA's researchers, no effort was expended in this work on calibration and validation of the simulation models used (FACET), since these issues were addressed in previous studies.

The analysis was conducted using simulated traffic data for particular days when restrictions were used to reroute and meter certain NAS flows. Traffic data (aircraft radar-tracked positions) were obtained from NASA in the form of Enhanced Traffic Management System (ETMS) data, for 11 days in August and September of 2002. Command Center logs for the days were made available through NASA in electronic form. These logs indicated what restrictions were imposed on each day. In addition weather condition and predictions on the days analyzed were obtained through the

[1] The deviation from the restrictions is due to a number of reasons including human error and the non-dynamic nature of the restrictions.

NEXRAD website (www4.ncdc.noaa.gov). The traffic demand was then run through simulations that represented the operations under TFM R&D tools and under current procedures and their performances were compared. The scenarios were selected to contain the restrictions needed for manifesting the benefit mechanisms of TFM R&D tools. For example, the analysis used days when some NAS traffic flows were impacted by a flow constrained area (FCA) such as severe weather. Some routes have been impacted (possibly closed) due to the FCA and FAA TFM initiatives (such as reroutes) were put in place in response. These FAA TFM initiatives were then simulated to provide a baseline. Then alternative system (FAA and airline) responses to such a congestion problem, with the decision support of TFM R&D tools, were modeled and simulated, and compared to the baseline performance. The details of such modeling are presented under each benefit mechanism separately in Section 5 and the results are presented in Section 6.

2.3. Economic Performance, Sensitivity Analysis, and Extrapolation

As shown in Figure 1, the technical performance of the system is converted into economic terms, and the economic benefits of TFM R&D measured. The analysis is then tested through sensitivity analysis to identify the sensitivity of the benefit estimates to certain model and benefit mechanism parameters. The analysis is also extrapolated for extension to other years, so that the economic benefits of TFM R&D can be identified for an extended period of time.

For the assessment of the TFM R&D tools benefits in year 2015, a simulated baseline that represents the operations without using TFM R&D tools in year 2015 was compared with simulated operations with using TFM R&D tools in year 2015. The simulated 2015 operations should account for differences from current operations, as possible. For this study only increase in demand according to the FAA forecasts was simulated. The extrapolation is described in Section 9.

2.4. Modeling Tools

Since FACET is the basis of the TFM R&D tools (both SWEPT and FACET-AOC) it was used as the main simulation tool for the analysis of the TFM R&D benefit mechanisms. There are two possibilities for implementing the models representing the TFM R&D tools benefit mechanisms as shown in Figure 3: Either modifying and adding additional code inside FACET or modeling the benefit mechanisms externally (using external tools such as MATLAB or using a manual selection process) and interfacing with FACET through its inputs and outputs. For example, the inputs may be alternative traffic scenarios with flight plans modified according to the improved TFM programs; or they may be TFM programs that are selected externally and input to FACET through its user interface to be simulated.

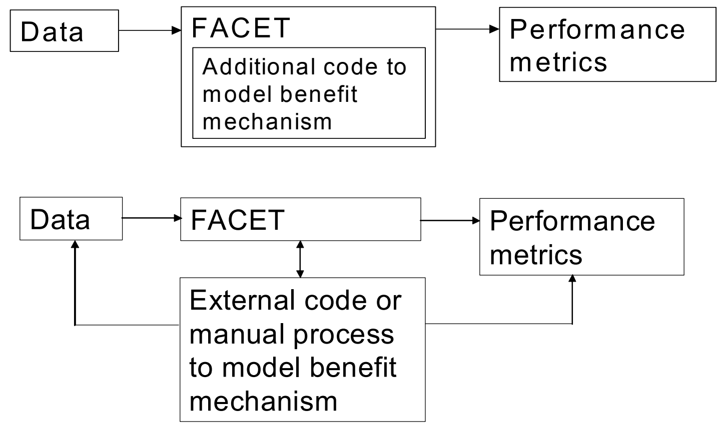

Figure 3: Modeling tools for TFM R&D benefit mechanisms.

Due to time constraints, it was attempted to avoid coding any models inside of FACET. The general approach was to use MATLAB to code the algorithms needed to represent the TFM R&D benefit mechanisms, or to manually select alternatives to represent TFM R&D benefit mechanisms after simulating in FACET. Details will be addressed separately for each benefit mechanism in Section 5.

3. Identification and Modeling of Current Operations

The performance of the NAS under current operations and TFM procedures is to provide a basis for comparison with the predicted system performance under TFM R&D tools. Therefore, in order to identify the benefits of TFM R&D, the current NAS operations and current traffic flow management procedures must be well understood and their limitations identified. This section describes the current NAS operations in terms of capacity constraints, traffic demand, and traffic flow management procedures; and the way they were modeled for the purpose of this benefits assessment.

3.1. Capacity Constraints

Resources in the NAS such as airports and airspace sectors and fixes, have capacity limits that constrain the flow of traffic through them. These capacity limits are dependent on many factors such as safety requirements and inclement weather. The capacity limits of two key NAS resources, airport runways and airspace sectors, are discussed below in terms of their modeling and measurement.

3.1.1. Runway Capacity Constraints

The primary flow constraints in the NAS are usually the airport runways characterized by their acceptance rate (AAR), which is the number of aircraft that are possible to land at an airport in an hour. In order to avoid excessive delays and congestion in the airspace, the ATC facilities' traffic management units attempt to maintain the demand below the AARs. The AAR is, therefore, one of the main parameters that are used in the process of traffic flow management.

The AAR depends mainly on the runway configuration, visibility, and runway conditions. The acceptance rate of an airport is usually reported by the airport control tower and changes according to runway configuration and airport conditions. The scenarios analyzed in this benefits assessment, while involved possible improvement in the utilization of the airports acceptance rate, concentrated primarily on rerouting, and did not involve increasing the airports acceptance rate as a parameter (see Section 5).

3.1.2. Sector Capacity Constraints

Airspace sectors have limited ability to hold and delay aircraft within their boundaries due to workload constraints and safety separation requirements. The capacity limit of each specific sector is characterized by the Operationally Acceptable Level of Traffic (OALT)[2], which is the maximum number of aircraft that can be within the sector at a given time. The traffic management units in the ATC facilities attempt to maintain

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[2] According to correspondence with a TMC, the OALT is a number agreed upon by a member from management (usually the Area Operations Manager) and Area NATCA representatives.

the number of aircraft within each sector (sector loading) below the sector's OALT, through rerouting and delaying aircraft. Therefore, the sector capacity limits are important parameters in the traffic flow management process.

As described in [2] a number of factors affect the capacity of sectors under normal weather conditions, such as: Complexity of flow patterns including climbs and descents, proximity of flows limiting vectoring ability, compression due to speed reduction such as during descent within the sector, limited real estate capacity to hold aircraft, wind direction where tail wind reduces the ability to space aircraft using speed reduction and vectoring, and gridlock possibility due to interdependence between flows and particularly between arrival and departure streams.

The sector capacity limits may be reduced further by outside events such as inclement weather restricting access to an airspace region, or outages.

Since the sector capacity is an important decision parameter in the rerouting of traffic and the propagation of delays, it is essential to identify the sector capacities in order to model the current baseline traffic flow management operations and the improved operations under TFM R&D tools. Sector capacities may be specified by the OALT, the maximum number of aircraft that can be worked in a sector at any given time. One representation of this number is the Monitor Alert Parameter (MAP)[3], which corresponds to the OALT and in used by the Monitor Alert Program to alert the traffic management personnel when the actual sector loading of any sector exceeds the MAP value. MAP values for all sectors were available in FACET for this benefits assessment.

Actual sector capacities can be identified from statistical analysis of historical data, by plotting the distribution of the number of aircraft in a given sector and selecting a high percentile as a representation of the operational maximum. This percentile value can be compared to the MAP value reported in FACET for the same sector. This analysis was performed in previous studies such as RTO 71 [1], which showed that the MAP values reported in FACET corresponded mostly to the 99th percentile of the historical distributions of the sector loadings. Therefore, it was decided that the MAP values reported in FACET were suitable for use in this benefits assessment.

3.2. Traffic Demand

The demand for the NAS resources is driven by the airlines scheduling of flights into and from airports. The demand at any fix or sector en-route to the destination airport can be represented by a series of Estimated Times of Arrival (ETA) calculated based on the airline schedules and flight plans. If unimpeded, aircraft fly from fix to fix at speed. Using unimpeded transition times between fixes, estimated times of arrival (ETAs) can be calculated at each fix, and at the airport as shown in Figure 4.

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3 According to correspondence with a TMC, the OALT number is incorporated into the Monitor Alert. Another representation of the OALT is therefore the Monitor Alert Parameter (MAP). The Monitor Alert Parameters (MAP) can be adjusted by ±3 aircraft by traffic management for various traffic management issues. Many times the numbers identified for a specific sector are incorrect – a known shortfall of the Monitor Alert Program.

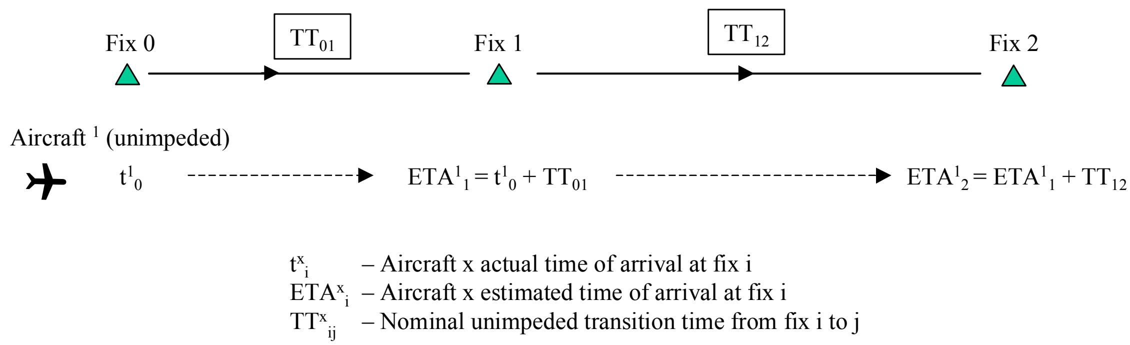

Figure 4. Demand based on estimated times of arrival

ETAs at fixes are calculated according to a flight's initial conditions, including time of entry into the system (t_0) and unimpeded transition times (TTs) between subsequent fixes in the flight plan as shown in Figure 4. In this manner each flight's ETAs can be calculated for all the applicable points, working downstream from the system boundary to the runway threshold.

In this study transition times are calculated using FACET, which generates trajectories between fixes specified in a flight's flight plan. By inputting each flight's flight plan into FACET, therefore, estimated times of arrival are calculated according to detailed trajectories, at each fix, at boundaries between airspace sectors, and at the destination airports.

3.3. Traffic Flow Management Procedures

In order to maintain safe, expeditious, and orderly traffic, the traffic flow management units of the ATC facilities attempt to maintain the demand at airports below the acceptance rate and the number of aircraft within sectors below load capacity. This is accomplished through a number of traffic flow management programs. Some TFM programs are used at the strategic level by the Command Center (ATCSCC) and some are used at the more tactical level by the air route centers (ARTCC), TRACONs, and control towers. These TFM programs include mainly:

Rerouting around flow constrained areas (FCA) of the airspace that are impacted, for example, by severe weather. These reroutes are strategic and global in nature and are usually applied by the Command Center according to common reroutes that are collected in either the Playbook or Coded Departure Routes (CDR). Local rerouting or **offloading** is also often applied by local facilities (ARTCCs) to avoid sector overload or holding.

The **Ground Delay Program** (GDP), which is a strategic temporal restriction that attempts to reduce the demand at airports below the expected AAR by delaying aircraft on the ground before departure. The Command Center assigns Expected Departure Clearance Times (EDCTs) to departures given the expected AARs conveyed by the airports (Control Towers / TRACONs).

Ground Stop (GS), which is used by the Command Center to produce an immediate impact by stopping the traffic to a destination impacted by reduced AAR.

Miles In Trail (MIT), which are used tactically by the air route centers (ARTCC) and TRACONS to reduce the congestion locally and maintain acceptable workload levels. Often MIT are associated with metering the arrival flow to destinations with low AARs and with the excessive sector loading that results from rerouting programs.

Departure Spacing Programs (such as DSP or APREQ), which are used by local facilities (ARTCCs and Towers) to insert departures into an overhead stream in a timely and orderly fashion. A departure takeoff time is assigned such that a departure is inserted into an available slot in the overhead stream. DSP is often used to control merging into a stream that is congested and impacted by MIT.

Holding, which is usually an extreme action that is used when acceptance of traffic into a downstream facility is denied. However, holding is used intentionally in some cases, such as in a managed reservoir where a certain number of arrivals are held in the close vicinity of the destination airport in order to maintain demand pressure on the runways and avoid starving them.

Based on research conducted by NASA's TFM R&D researchers (milestones 8.901.3 and 8.901.4 [3, 4]) a number of limitations were identified in the application and interaction between these TFM programs. These limitations may be summarized in the following items:

1- There is **limited integration** of FAA decisions on different TFM initiatives. For example, as mentioned above global reroutes are applied in order to avoid flow constrained areas such as severe weather. Then temporal restrictions such as Miles In Trail and holding are applied in order to mitigate the congestion and high workload resulting in the airspace sectors along the new routes. And finally further local reroutes may be used to offload aircraft from any remaining congested sectors. These actions are performed mostly in a serial fashion and may be improved with increased integration, such as taking into account the resulting congestion while making the rerouting decisions.

2- There is **limited ability to predict NAS problems and assess solutions** accurately leading to over conservative restrictions. The main difficulty in making traffic flow management decisions is lack of accurate weather prediction. However, given the available accuracy in weather prediction, the traffic managers lack sufficient ability to predict the effect of their actions accurately. This ability may be improved through predictive models of traffic in response to different TFM actions and to different NAS congestion scenarios.

3- There is **limited cooperation between the FAA and the airlines** in making traffic flow management decisions. A number of examples of potential improvement in traffic flow management through airline involvement are given in [4]. For example, there is need for more reroute options in line with airline objectives (schedule adherence). There is need for more pre-emptive airline actions that reduce the NAS congestion and reduce the need for FAA intervention and restrictions. There is also need for common situation information and integrated rather then conflicting solutions, between the FAA and the airlines and between different airlines.

4. TFM R&D Functional Analysis

TFM R&D (SWEPT and FACET-AOC) is currently at a low technology readiness level (TRL 2-3). Most of the TFM R&D functions are currently envisioned ideas that were extracted through expert interviews [3][4]. Some of these functions are already developed in software to a certain degree, such as SWEPT's playbook reroute conformance monitoring and FACET's analysis functions such as sector count. However, even these somewhat developed functions are currently initial developments intended for user feedback and further definition and extension based on the feedback.

Because of the early stage of development of TFM R&D and the lack of clear and detailed definition of an operational concept, a wide range of functions may be identified. This range is made even wider if it is to include envisioned extensions in addition to existing functions – TFM R&D (SWEPT and FACET-AOC) is considered by its NASA developers to be an extensible set of tools where new functions can be added as needed and where deemed beneficial. However, due to time and funding limitations, a subset of functions needed to be identified for analysis. Therefore, an initial task in this study was an attempt to identify an initial comprehensive list of functions of TFM R&D, and then prioritize this list in order to extract the subset of functions to further pursue in the benefit assessment effort.

This section presents this functional analysis effort resulting in the main functions of TFM R&D that were analyzed in this study. A number of functions were identified according to documents, provided by NASA, detailing the TFM and AOC assessment of FACET utility [3][4], and according to the analysis utilities currently available in FACET. In order to prioritize the functions, potential benefit mechanisms and benefits were identified, and then NASA's researchers were consulted to provide their prioritization of the identified functions. The following functions were identified by NASA TFM R&D researchers to be the most important, and were thus chosen for further analysis:

- SWEPT decision support in solving Flow Constraint Area (FCA) problems.
- SWEPT decision support in solving airspace design and resectorization problems.
- FACET-AOC decision support in airline response to congestion, particularly preemptive actions by the airlines.

Both these and the functions not prioritized are described below. However, details on benefit mechanisms and modeling are presented in Section 5 only for the three functions identified above.

4.1. Function Categorization according to Decision Making Process

The initial functional analysis and functions' benefit assessment is conducted based on categories of functions. By categorizing the functions the analysis may be focused on assessing the benefits of a smaller number of categories of functions. Each category may include a wide range of specific functions that may achieve an overall purpose. A representative of the type of function that falls under a category would be sufficient for modeling and analysis, with appropriate extrapolation if needed.

By listing the different operation experts' suggestions for the use of SWEPT and FACET-AOC [3][4], and by listing the different existing analyses in SWEPT and FACET, a number of categories of functions were identified. The function categories that were identified mirror the tasks that constitute the decision making process of a TFM decision maker, both on the FAA ATM and the airline sides. These decision-making tasks are as follows:

- Collect and share information
- Predict future behavior
- Identify problems
- Generate alternative solutions
- Evaluate alternatives and select appropriate solution
- Monitor and evaluate system performance

4.2. Operation Mode, Time Scale, and Automation Level

Different operation modes, time scales, and automation levels were also identified according to the analysis of the operations expert suggestions [3][4], the current FACET and SWEPT analyses, and feedback from NASA's TFM R&D researchers.

Providing support to the decision process may occur in two modes: a real-time mode and an off-line mode. In real-time mode, support is provided to resolve and prevent traffic flow problems as they occur and are predicted to occur in real time. In off-line mode, support is provided to address traffic flow problems after they had occurred in order to prevent their occurrence in the future. The real-time mode typically supports operations within a daily cycle, analyzing the past few hours, predicting in the next few hours, and making decisions with an impact mostly lasting within the current daily cycle. The off-line mode typically supports operations beyond the daily cycle, analyzing historic operations and making decisions that affect future operations well beyond one day. However, the same analysis may be used in both the real-time mode as well as the off-line mode, depending on what data and time period it is applied to.

The decision process also occurs on different time scales. For example in the real-time mode three time-scales are typically found in the literature: tactical, strategic, and preemptive, which respectively have typical values of 1 hour, 2 to 4 hours, and 4 to 6 hours in advance of the predicted problem situation. In the off-line mode multiple time scales can also be thought off. For example: days versus months versus years.

When applying decision support to the decision process there are also a number of automation levels. The automation level increases as decision support is provided to more versus fewer of the decision process tasks. The automation level also varies when decision support is applied to each task of the decision process; for example, a computer may perform a task upon a request from the human user (resulting in "what if" type support) or completely automatically (resulting in alerting type support, by alerting the user without waiting for a request).

Therefore, each category of functions (which represents a major task of the decision making process) shall be analyzed by considering its different uses along the three dimensions: real time and off line modes, different time scales (tactical, strategic, and preemptive), and different automation levels (no automation, partial automation e.g. what if support, and full automation).

4.3. Identification of Main Function Categories

Using the different tasks of the decision-making process, and the different modes, time scales, and automation levels for each task, results in a formal procedure for the identification of the TFM R&D functions. In this formal procedure, the existing TFM R&D functions are classified in categories according to the tasks and the different modes and scales. In addition, non-existing functions or categories of functions that may be envisioned as extensions to the tool set are also identified. In other words the formal procedure allows a more comprehensive function analysis.

Each functional category has four attributes, task type, operation mode, time scale, and automation level. Each attribute may have a number of different values as shown in the example below:

- Task type:
  - Information collection/sharing
  - Prediction/simulation
  - Problem identification
  - Solution alternatives generation
  - Solution evaluation and selection
  - Monitoring and evaluation
- Operation mode:
  - Real time
  - Off line
- Time scale:
  - Tactical
  - Strategic
  - Preemptive
- Automation level:
  - Manual
  - Upon request (What if)
  - Fully automated

A large number of categories would result if all combinations of the four attributes existed (72 categories would result for 6 tasks, 2 modes, 3 time scales, and 2 automation levels). However, only the combinations that make operational sense will be considered. For example, it is irrelevant to consider automation in the off-line operation mode (the off-line mode is always upon request and not fully automated). In addition, the number of functions (or categories of functions in this case) does not correspond directly to the amount of analysis and simulation needed. Rather, it is the benefit mechanisms that are simulated. A function may simply be an enabler of another function, and multiple functions may contribute to a single benefit mechanism. In attempting to be comprehensive in identifying functions, the goal is to be comprehensive in identifying the benefit mechanisms that result from these functions. In the following each decision task type was analyzed under different operation modes, time scales, and automation levels. Operationally relevant categories were maintained and irrelevant ones discarded. The remaining categories were analyzed further and prioritized in terms of their potential for deriving benefit mechanisms.

4.4. TFM R&D Function Categories

The following are the main identified function categories of SWEPT and FACET-AOC outlined according to the task type and the other attributes (operation mode, time scale, and automation level). Each function category will be described briefly, examples of existing or envisioned functions under the category detailed.

4.4.1. TFM R&D Information Collection and Sharing

One basic function of SWEPT and FACET-AOC is providing information to the TFM and AOC decision makers, respectively. The current version of SWEPT is being developed to use ETMS as its source of information for integration with the air traffic system's information network. Therefore, most of the information available through ETMS (except sensitive information) is (or can be made) available through SWEPT. Similarly, FACET-AOC uses Aircraft Situation Display for Industry (ASDI), which is filtered ETMS data for use by the industry, as its main source of information. However, the set of information that SWEPT and FACET-AOC provide includes but is not limited to the information set available through ETMS[4].

ETMS is mainly a source of traffic and weather data. Traffic data include one-minute updates of radar tracks collected from all ATC facilities, including some Canadian, Mexican, British, and oceanic. Traffic data also include flight plans and flight plan amendments. Weather data include wind (one hour updated RUC data), and convective weather (CCFP).

ETMS, and hence SWEPT, also provide information about airline actions through the Collaborative Decision Making (CDM) stream. This information includes (at least) cancellations, updates to flight plans, and updates to estimated departure times. This information would allow SWEPT a role in collaboration between TFM decision makers and airline operations decision makers.

In addition, SWEPT and FACET-AOC (either through ETMS or tapping directly into other sources) provide information about the TFM restrictions, in place or planned. For example, SWEPT is already integrated with the National Playbook Reroute database.

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[4] According to NASA's researchers, tying SWEPT to ETMS is needed in order to integrate SWEPT into the ATC network, but does not imply that SWEPT may not be linked to, and provide information from, sources other than ETMS. For example, FACET, the basis on which SWEPT is built, is able to obtain weather information from internet sources.

When a playbook reroute is planned or is in effect it is currently manually entered, but may be automatically entered into SWEPT in the future with the proper connectivity. Although the other TFM programs have not been integrated into SWEPT, FACET is able to take most these initiatives as input and simulate their impact. It is reasonable to assume that SWEPT, with proper connectivity, will receive and provide information about the TFM initiatives (in effect or planned) such as Ground Delay Program (GDP), Ground Stop (GS), Miles In Trail (MIT), and possibly airport acceptance rates (AAR) and airport and airway closures. Providing the airlines with information about the TFM initiatives planned by the FAA allows FACET-AOC to assist in the collaboration between the FAA TFM and the airlines decision makers.

Therefore, the list of information that SWEPT and FACET-AOC may provide is:

- Traffic information (track and flight plans)
- Weather information (wind, radar, convective)
- Airline information (cancellations, departure times)
- TFM restrictions (reroute, GDP, GS, MIT, AAR and closures)

Operation mode – Information collection and sharing through SWEPT and FACET-AOC is a real time mode function that helps visualize and analyze current operations. SWEPT displays traffic and weather information in real time on a display that is made as identical to the Traffic Situation Display (TSD) as possible. This ensures compatibility and standardization purposes, and is intended to eliminate any confusion of the users that may be looking at both systems[5]. In off-line mode it is possible to playback past information (tracks, weather, and restrictions) in order to visualize and analyze past operations.

Time scale – The time scale applies here to the act of making a decision a certain time prior to an event, and it is therefore, not relevant to information collection.

Automation level – One may think of providing information upon request or automatically; for example, the user may turn the display of weather on and off, or request airline cancellation information.

Therefore, the function categories under information collection and sharing are:

- Off line, information playback
- Real time automated information display
- Real time information request

Providing information is a basis for most other functions of SWEPT. For example, based on the information available, SWEPT provides prediction and identifies flow constraint problems. Information collection and sharing is therefore mainly an enabler of other SWEPT functions. Therefore, benefit mechanisms would be indirectly related to information collection and sharing through other functions (such as prediction and problem identification) that are enabled by information collection and sharing. These benefit mechanisms would be analyzed in detail under these other functions and not

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[5] FACET adds certain display features that may not be available in TSD. For example, FACET has a capability to display maps and traffic in a three dimensional view.

under information collection and sharing. However, when identifying the benefit mechanisms of the other functions, it should be kept in mind that information sharing enables collaboration between the FAA and the airlines when performing these other functions. For example, if SWEPT provided airline information to TFM decision makers, then they may be able to perform more informed decisions about TFM initiatives that take the airlines actions and preferences into account.

4.4.2. TFM R&D Prediction and Simulation

The prediction capability of SWEPT and FACET-AOC is based on FACET's trajectory generation for en route flights. FACET also has a capability to predict departure times using airport-based statistical models. Using the simulation capability FACET is able to take as an input a number of TFM initiatives and simulate the NAS operations under their effect. It is also able to take as input changes in the NAS boundaries.

Operation mode – The same prediction/simulation capability may be used in real time to assist planning functions, and in off-line mode to assist evaluation of past operations (for example under different actions and initiatives).

Time scale – Prediction may also be over different time horizons.

Automation level – Prediction may also be either automatic or upon request.

These different modes however, will not be fully explored because prediction and simulation is considered an enabler of other functions. No explicit benefit mechanisms will therefore be drawn from the prediction and simulation function explicitly.

4.4.3. TFM R&D Problem Identification

There are a number of metrics that FACET currently computes to identify constraints in the NAS that may impact traffic flow performance. These metrics may be utilized by both SWEPT and FACET-AOC and include the following:

- Sector overload, using sectors count or dynamic density measures, the instantaneous or predicted number of aircraft in a sector is compared to a threshold (MAP). If the maximum threshold is violated the sector is displayed in red alerting the decision maker. The thresholds are typically representative of maximum controller workload in a sector. They may be reduced also to represent reduced sector capacity under adverse conditions such as severe weather or equipment outage.
- FACET also measures delay with respect to the schedule (ETA). Delay may also be used as an indication of flow constraints in the system because they result whenever demand exceeds capacity. Because FACET has the capability to predict departure times, and to compute sector crossing times, it is also possible to determine the distribution of delay through the NAS by measuring the delay associated with particular sectors.

- FACET has a conflict detection capability. As was indicated by NASA's researchers, conflict detection may be used to identify flow problems related to the NAS design and therefore, impact flow management at a higher level.
- Although currently non existent in FACET, other measures may be easily incorporated, such as identifying holding aircraft and comparing an airport schedule to its acceptance rate, that add to the capability of identifying flow constraints.

FACET has also a Flow Constraint Area (FCA) capability. The FCA is a box that bounds an area of the NAS that may constrain the flow. This area may be drawn manually (for example around severe weather areas); however, automated identification of FCAs may be envisioned given connection to appropriate data sources. Sectors that are overloaded may be considered FCAs. Military or restricted areas as well. The FCA capability allows SWEPT and FACET-AOC to provide planning support in order to avoid the FCA or mitigate its effect.

Therefore, whether using aircraft count, delay level, or conflicts rate, SWEPT has a capability to identify major and secondary flow constraints (bottlenecks) in the NAS. These are resources that have demand higher than capacity, either due to increase in scheduled demand or due to reduction in capacity under adverse weather conditions for example. The constraint may be an overloaded sector, an overloaded airport, a severe weather impacted area, or even a badly designed airspace area. Similarly FACET-AOC is capable of identifying these constraints and their impact on a particular airline. Abstractly, and in order to limit the scope of the analysis, two types of constraints will be considered for SWEPT: a flow constraint type problem that may be represented with an FCA and an airspace design and resectorization type problem. For FACET-AOC an FCA type problem represents the impact of congestion on a particular airline's flights in real time. FACET-AOC may also help airlines identify longer term type problems such as limitations in their schedules, flight plans and markets.

Operation mode – Real time mode may lead to different benefit mechanisms than off line mode. For example, off line constraint identification is more likely to influence airspace design and long-term procedure changes for the FAA and the airlines, while real time constraint identification helps in planning.

Automation level – There is no clear need to distinguish between constraint identification upon request or automatically.

Time scale – Time scale is certainly relevant to constraint identification. In the real-time mode identifying current constraints would support tactical planning, while predicting constraints in the future few to many hours would support strategic and pre-emptive planning. In off line mode constraint identification may support strategic plans and procedures that have days and months long effects, as well as procedures and airspace design that have much longer time effects.

Therefore, the different modes and attributes that may be considered for constraint identification are:

- Real-time mode, in tactical, strategic and pre-emptive time horizons
- Off-line mode, over possibly multiple time horizons also

Problem or constraint identification, as is the case in information collection and in prediction, mainly generates benefits by enabling other functions, namely generating and selecting solutions which are used to address and mitigate the constraints. However, in identifying the benefit mechanisms of the remaining functions both the FCA type problem and the airspace design and resectorization type problem will be considered for SWEPT. And for FACET-AOC both real-time FCA impacts on an airline and longer-term flight and schedule planning will also be considered.

4.4.4. TFM R&D Solution Alternatives Generation

There are two levels of automation: One lower level of automation that generates alternative solutions and that lets the human decision maker select one alternative; and a higher level of automation that selects the best alternative solution and presents it to the human decision maker as an advice. However, in order to limit the scope these two automation levels are not distinguished in this analysis. Therefore, this function category is combined with solution evaluation and selection (described next).

4.4.5. TFM R&D Solution Evaluation and Selection

As indicated in Section 4.4.3 two types of TFM problems are identified and will be considered for solution with the help of SWEPT: FCA type problems and airspace design and resectorization type problems. In addition the type of TFM problem that will be considered for solution with the help of FACET-AOC is airlines' real time and long-term response to the impact of congestion.

SWEPT decision support in solving FCA type problem

FACET has the capability to take flow restriction inputs and simulate their effects. These include reroute, Ground Delay Program (GDP), Ground Stop (GS), and Miles In Trail (MIT). It is therefore able to change flight plans according to reroutes, delay aircraft departure times according to GDP or GS, and slow down or hold aircraft to space aircraft according to MIT restrictions. These inputs are the existing TFM initiatives that are used in order to mitigate the effects of flow constraints. In other words they are the current possible solutions to identified flow constraints.

Automation level – These capabilities enable SWEPT to have what if type functionality to test and compare the performance of different TFM initiatives. Different initiatives may be compared as well as different locations and durations of the same initiative. The metrics available are as mentioned earlier, sector counts and dynamic density, and differential delay. Other metrics may be simply added such as throughput. With what-if functionality the human decision maker would select the best solution based on some objective function.

These same capabilities enable SWEPT to have internal fully automated functionality that generates the different alternative solutions (TFM initiatives and their location and duration), compares them, and selects the best solution based on some objective function.

However, in order to limit the scope of this task, there may be no need to distinguish between what if and fully automated functionalities. Since neither is currently implemented, the what if functionality will probably be implemented as a step towards the fully automated functionality. Also the benefit of both functionalities is in terms of selecting a better solution based on some objective function – this function may be of the human decision maker in the case of what if functionality and of the automation in the case of the fully automated functionality. In both cases some objective function needs to be modeled and the difference may not be distinguishable with high fidelity without more extensive research.

Operation mode and time scale – For an FCA type problem it is necessary to consider both the real time and off line modes of operation because they probably lead to different benefit mechanisms. For example, in real time SWEPT would assist in planning a combination of initiatives to mitigate the effects of the FCA. This may be done over different time scales, tactical, strategic and pre-emptive – since different initiatives are applied typically over different time scales. In off line mode SWEPT would assist in longer-term adjustments in TFM procedures and the design of the TFM initiatives. For example changing the playbook routes, enhancements in GDP, or even devising new initiatives such as time based metering to replace MIT.

Therefore, the different modes and attributes that may be considered for generating and selecting solutions for the FCA type problem are:

- Real time mode, over tactical, strategic and pre-emptive time horizons.
- Off line mode

<u>SWEPT decision support in solving airspace design type problem</u>

For the airspace design type problem, SWEPT (or FACET) has the capability to take as input changes in the NAS boundaries.

Automation level, operation mode and time scale – This capability allows what if functionality to test and simulate the performance of the NAS under different airspace designs in an off line mode of operation. This may also assist in dynamic resectorization in a real time mode. The metrics that would help are in addition to the sector counts and delay, the number of conflicts that may result under different sector designs. The time scale for this type of problem is most likely a longer strategic (or pre-emptive) time scale.

Therefore, the different modes and attributes that may be considered for generating and selecting solutions for the airspace redesign and resectorization type problem are:

- Off line mode for airspace redesign
- Real time mode for dynamic resectorization over strategic and pre-emptive time horizons (possibly)

<u>FACET-AOC decision support to airline's response to congestion</u>

Using the same FACET capabilities in simulating new routes and the effect of different FAA initiatives, FACET-AOC assists airlines in responding to congestion problems. Faced with a predicted congestion an airline may take actions to change flight plans around predicted FCAs, change the departure times, or cancel certain flights to give priority to other flights. The airline is able to simulate the effects of these actions on its flights. Then the airline is able to make decisions about the actions needed according to its own objectives.

Automation level – No distinction is made between a what-if and a fully automated functionality due to the same reasons mentioned for SWEPT.

Operation mode and time scale – This functionality may be performed in real-time mode in responding to currently predicted congestion, or in off-line mode in response to recurring NAS congestion patterns. In real-time, airline responses are typically initiated before departure time (in the form of cancellation, delay of departure time or re-filing of a route). If the airline actions were taken considerably early they would preempt the need for FAA initiatives, reinforcing the benefits to the airlines. In off-line mode, the airline may for example, redesign its flight plans, its schedule, and the market it serves, based on analysis of its historical performance is response to NAS flow constraints.

Therefore, the different modes and attributes that may be considered for generating and selecting airline responses to NAS congestion problems are:

- Real-time preemptive response to NAS flow constraints
- Off line mode for flight planning and scheduling

Since currently FACET-AOC is intended for use at the dispatcher level, only the real-time mode of operation will be considered for benefit assessment.

4.4.6. TFM R&D Monitoring and Evaluation

After a TFM program is put in effect SWEPT has the ability to monitor and evaluate the performance of the system. While there are a number of possible ways and performance metrics to monitor, the one monitoring function that is currently implemented in SWEPT is conformance monitoring – in which the conformance of the system, specifically to a playbook reroute, is monitored. Extension of this function to monitoring the system's conformance to other TFM initiatives such as GDP, GS, and MIT may be added. The metrics that are currently reported are the individual aircraft that are out of conformance in terms of their flight plan, and the ATC facilities (centers) and the airlines to which these aircraft belong. Aggregate measures such as total number of aircraft out of conformance in a center or of an airline are also reported.

Operation mode – This function is mainly a real-time function. SWEPT also has the capability to review and evaluate the performance of the system in terms of responding to a TFM program off line using historic data. Again this may be done for conformance monitoring to a playbook route as well as conformance to other initiatives in the future.

Automation level and time scale – Distinguishing between different time scales and between different automation modes (what if versus fully automated) will not be emphasized in the monitoring and evaluation function.

Therefore, only two modes will be considered for monitoring and evaluation:

- Real time monitoring and evaluation
- Off line monitoring and evaluation

Besides monitoring and evaluation of the system's conformance to the playbook reroutes and to other TFM initiatives, other system performance metrics may be monitored and evaluated. For example, SWEPT may monitor and evaluate how well a TFM initiative is achieving its intended goal in terms of matching demand and capacity, maintaining workload level, or maintaining high system capacity utilization. These other types of performance monitoring and evaluation are not implemented, although they may be envisioned as future extensions. These additional functions will not be modeled and their benefits will not be assessed.

Real time monitoring and evaluation for the airline was not mentioned in the expert comments [4] and therefore, will also not be considered for benefit assessment.

5. Identification and Modeling of TFM R&D Benefit Mechanisms

A formal method for mapping TFM R&D functions into benefits is outlined and used for the derivation of the benefit mechanisms. Benefit mechanisms of the three main TFM R&D functions identified for further analysis in Section 4 are derived and their modeling and analysis methodology are described in this section.

5.1. Approach for Identification of Benefit Mechanisms

For the purpose of clarity, consistency, and completeness, functions, constraints, benefits, and benefit mechanisms were formally defined in Section 2.1. The benefits of TFM R&D are identified by applying the functions of TFM R&D identified for further analysis in Section 4 to alleviate the NAS constraints and flow management limitations identified in Section 3. A function excites a benefit mechanism, which creates a benefit. The mapping of functions to benefits is not one to one, nor is there a consistent number of steps in each benefit mechanism.

Charts of the benefit mechanisms (mapping from functions to benefits) were developed to improve clarity and reviewability, and are included with the descriptions of the benefit mechanisms. The following definitions apply to the charts:

- Bold shaded blocks represent TFM R&D functions.
- Normal shaded blocks represents characteristics of the function from which they are extracted.
- Bold unshaded blocks represent quantifiable benefits.
- Normal unshaded blocks represent intermediate steps between a function and a benefit, which make up TFM R&D benefit mechanisms.
- Black blocks with white writing represent direct economic benefit (used in Section 5.3).
- An arrow (to a function) represents "enables" (i.e. one function enables another function)
- An arrow (to a benefit or intermediate step within a benefit mechanism) represents "results in" (i.e. one function results in a benefit)
- Dotted arrows represent an effect that shall not be modeled in this study. These benefits or benefit mechanisms may represent an effect that is not a current TFM R&D benefit, or benefit mechanism, but through enhancement of the functionality of TFM R&D, may become one.
- Merging arrows mean that more than one function or benefit mechanism enables or results in a particular function, benefit or benefit mechanism.
- Forking arrows mean that more than one function, benefit or benefit mechanism is enabled by or results from a particular function, benefit or benefit mechanism.

When a modeling parameter can be related directly to a box in the charts, the parameter is included in parenthesis below the block.

The functions of TFM R&D for which benefit mechanisms are described are:

1. SWEPT decision support in rerouting around a Flow Constraint Area (FCA).
2. SWEPT decision support in airspace design and resectorization.
3. FACET-AOC decision support in airline response to congestion, particularly preemptive actions by the airlines.

Benefit mechanisms for each of the three TFM R&D functionalities are described in detail below. A single chart is presented for each function followed by a description of each mechanism enabled by the function under consideration. Following the description of each mechanism, a section is included under each function giving an overview of the modeling methodology.

5.2. Benefit Mechanisms and Modeling of Rerouting Around FCA

As discussed in the functional analysis, SWEPT may assist in solving rerouting around an FCA in either real time or offline modes of operation.

In the offline mode SWEPT assists using historical analysis of FCA problems in the redesign of current TFM initiatives, such as the development of new reroutes for the National Playbook, and the development of time based metering. The new TFM alternatives could then be implemented in rerouting around an FCA using SWEPT in real time. The offline mode of SWEPT thus increases and improves the alternative solutions available for the real time mode, based on historical analysis. Therefore, the benefit mechanisms of the analysis of rerouting around an FCA using SWEPT offline materialize through reinforcing the benefit mechanisms of the real time mode; and therefore, the benefit mechanisms identification and modeling will focus conservatively on the real time mode.

By applying SWEPT functions to alleviate the limitations in the current TFM procedures described in Section 3.3, three primary benefit mechanisms will be considered for rerouting around an FCA using SWEPT in real time. The first is improved rerouting by enabling the Command Center to test and simulate different reroutes and reroute modifications, from a set of FAA reroute alternatives such as the Playbook. The second is improved rerouting through enabling collaboration with airlines, allowing the airlines to suggest and request to replace the FAA reroute selection by their preferred reroutes to avoid the FCA. And the third is improved rerouting by enabling an integrated TFM approach integrating rerouting with temporal metering decisions. These three primary benefit mechanisms are discussed in detail below.

5.2.1. Benefit Mechanisms of using SWEPT for Simulation and Comparison of Different Reroutes

SWEPT provides, with its simulation engine, a tool for reroute assessment and a more flexible reroute selection. Using SWEPT the Command Center will be able to simulate and compare the effects of alternative reroutes from the playbook, reroute combinations, reroute modifications, and reroute durations. This enables a number of benefit mechanisms as shown in Figure 5 below. These benefit mechanisms include selecting shorter reroutes, a more balanced loading of flights among reroutes, a more accurate identification of the set of flights that need to be rerouted, and a more accurate duration of reroute application. With a prediction of the FCA progress in time, which SWEPT is expected to include, the reroute selection may be optimized accounting for the uncertainty in the FCA progress over time.

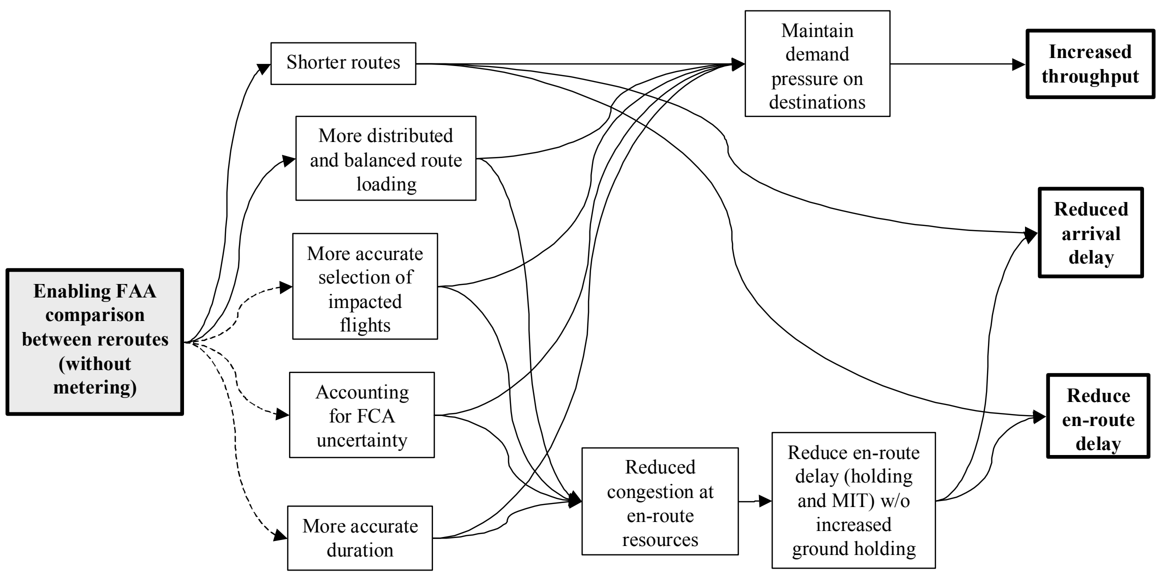


Figure 5. Benefit mechanisms of using SWEPT for comparing and selecting reroutes.

Combined, these mechanisms lead to benefits through a less conservative, but still safe, selection of the reroute. For example, when possible, SWEPT should allow avoiding the FCA safely with shorter routes, better allocation of flights over reroutes, shorter reroute duration, and a smaller set of rerouted flights. These mechanisms avoid loss of capacity, as higher demand pressure is maintained on the destination airports and throughput is increased. Shorter reroutes also reduce en-route delay as well as arrival delay relative to the schedule.

These mechanisms also lead to benefits through causing less congestion on the NAS resources through which flights are rerouted. With SWEPT, it will be possible to simulate the alternative reroute scenarios and determine the corresponding congestion and sector loadings. Then, the reroutes, the number of flights rerouted, the allocation of flights to reroutes, and the duration of the reroutes, can be selected based on reduced congestion and sector loading.

The need for holding and MIT restrictions to mitigate the congestion caused by the playbook reroute is thus reduced. A result of this is reduced en-route delay. Because this response does not delay the departure of the flight any later than originally scheduled, en-route delay is reduced without increasing ground delay. Thus, arrival delay, which includes en-route delay and ground delay, is also reduced.

5.2.2. Benefit Mechanisms of using SWEPT for Integrated TFM

SWEPT enables the integration of a number of TFM responses to congestion. For example, Sridhar describes in [5] a three-tiered approach to solving the FCA problem. Tier one is a global reroute to avoid the FCA spatially. A result of this reroute is a high volume of traffic passing through new sectors, which can cause congestion in these sectors due to already existing traffic passing through them. Temporal restrictions therefore form the second tier, with the function of metering the increased traffic flow in these congested sectors. Local reroutes form the third tier in assisting the temporal restrictions in preventing any remaining sector overload. Local reroutes refers to the tactical rerouting of selected flights around a congested sector, and constitutes in effect an offloading of these flights to adjacent sectors that may have lower loads.

One example of integration of these TFM responses allows making the rerouting and associated temporal metering decisions for each flight based on the combined effects of both types of restrictions: rerouting and metering. This results in improved effectiveness of each of the responses as they are applied in accordance with each other, and not independently. The benefit mechanisms of these improvements are detailed in Figure 6 and described below.

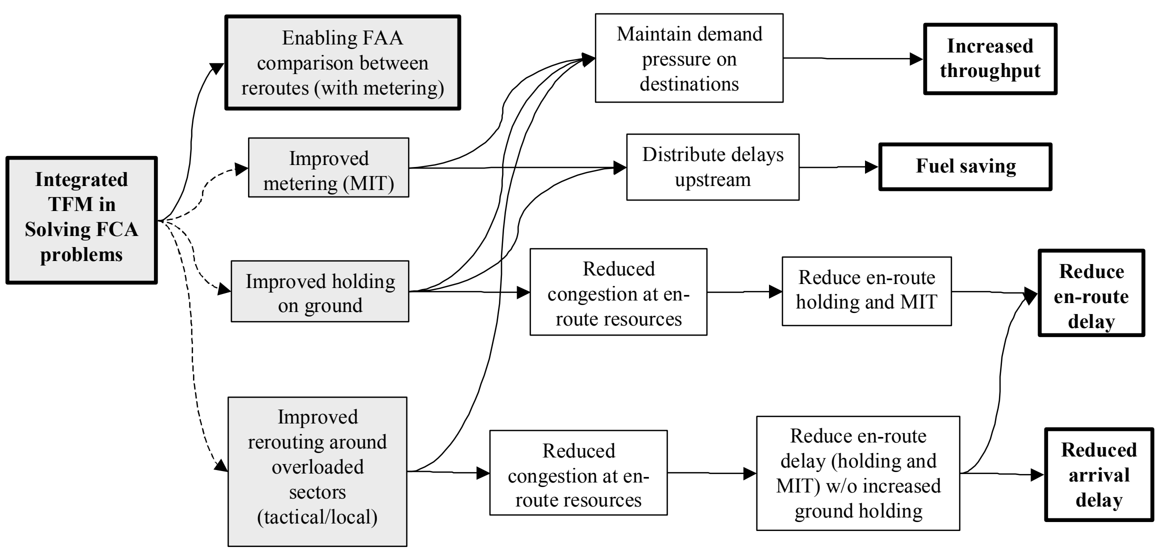


Figure 6. Benefit mechanisms using SWEPT to enable integrated TFM.

The integrated approach to TFM enables simulation and comparison of alternative reroutes based on the combined effects of route distance and temporal metering due to congestion. This results in enhancing the benefit mechanisms that are covered in Figure 5. Each of these benefit mechanisms was discussed in detail above.

Improved metering, such as by better MIT restriction selection, can also allow for more efficient distribution of delays as restrictions are propagated upstream. If the FCA is located far downstream, such as on a Standard Terminal Arrival Route (STAR), propagation of the delay upstream will result in a fuel saving. This is because more fuel is burned at low altitude than at high altitude. Similarly if an FCA affected departure routes out of a TRACON, better MIT (possibly combined with DSP) would result in fuel saving by holding aircraft on the ground instead of in the air. In addition by using SWEPT to simulate the effect of alternative MIT restriction values more efficient and less severe MIT may be selected, resulting in increased throughput.

By simulating different ground holding scenarios (different programs such as GDP, GS, or DSP, their locations, and their durations) it is possible to select the combination that results in higher throughput and least delays. Higher throughput results from maintaining higher demand pressure at the restricted destination airports.

The holding of aircraft on the ground, be it through a ground delay program, a DSP, or through a ground stop, results in accumulation of some delay at the origin airport (which is essentially a distribution of delay upstream). Savings in fuel burn result because less fuel is burned while the aircraft is on the ground.

The holding of aircraft on the ground can also result in reduced congestion at the en-route resources as the flights through these resources are separated more over time. This results in a reduction in the en-route holding and MIT restrictions required to mitigate congestion at these resources. The result of this is reduced en-route delay, which would have been incurred had the aircraft flown according to the original schedule. Although en-route delay is reduced, ground delay may be increased, and arrival delay is thus not necessarily decreased.

Improved tactical or local rerouting of some flights around a congested sector (which became congested due for example to a playbook reroute) results in a reduction in the sector congestion, as some flights are offloaded more effectively to less congested sectors. Required en-route holding and MIT restrictions to mitigate the congestion are thus reduced, and this results in a reduction in en-route delay. Because the restrictions are reduced without any increase in ground holding flight arrival delay is also reduced. Offloading may also result in an increase in system throughput by maintaining higher demand pressure at destinations.

5.2.3. Benefit Mechanisms of using SWEPT for FAA and Airline Collaborative Rerouting

In addition to assessing different FAA reroutes, a collaborative rerouting scheme is enabled by SWEPT whereby the airlines may be able to suggest and be granted reroutes closer to their preferences. Using SWEPT for collaborative rerouting around an FCA, where reroutes are allocated through CDM with the airlines, results in a number of benefits as shown in Figure 7 below.

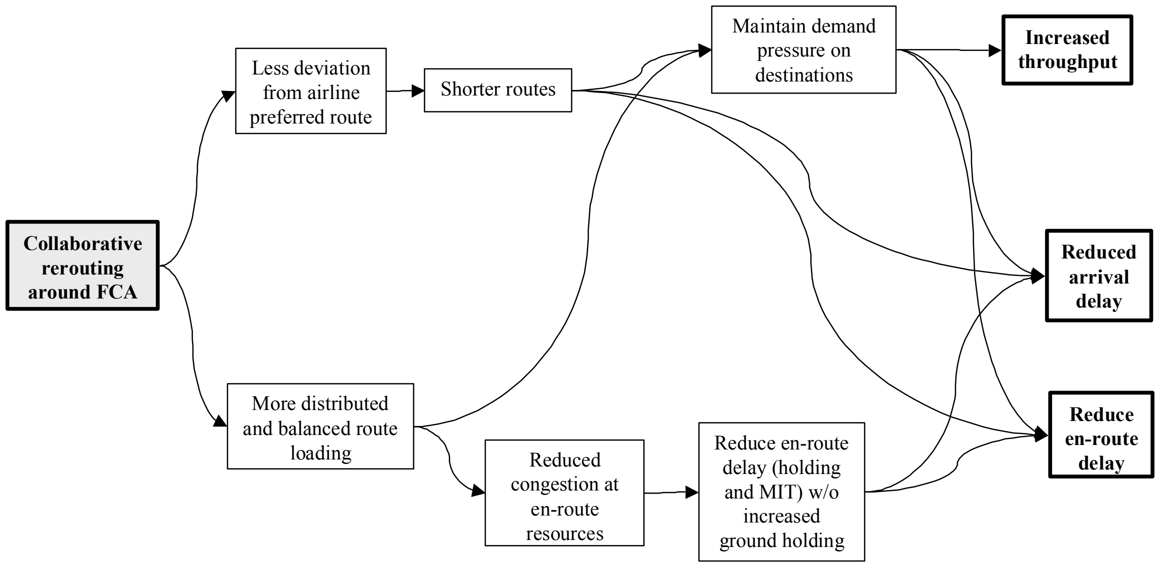


Figure 7. Benefit mechanisms of using SWEPT for FAA and airline collaboration in rerouting.

Collaborative rerouting around an FCA will reduce flight deviation from airline preferred routes, as airlines are able to choose reroutes according to their own priorities. This leads to shorter routes as long as the airline preferred routes are shorter than the FAA selected reroutes. Shorter routes lead to benefits in terms of increased throughput and reduced en-route and arrival delays as indicted in Section 5.2.1.

Collaborative rerouting also enables a more distributed and balanced loading of flights on reroutes, as less flights will follow the congested reroute selected by the FAA. This will result in a reduction in en-route congestion and correspondingly reduction in the need for mitigating the congestion through temporal restrictions. As indicated in Section 5.2.1 this results in reduced en-route delay and arrival delay, which respectively reduce airlines operating costs and improve their on-time performance.

5.2.4. Modeling Methodology

The modeling described in this subsection incorporates both the improved rerouting enabled by SWEPT, including selection of better reroutes through simulation and comparison, collaborative rerouting between airlines and the FAA, and the integration of the TFM initiatives of global rerouting and metering. Due to time and resource limitations, the modeling and analysis was focused on the improvement in the rerouting and the temporal metering associated with the rerouting. It did not address improvement in temporal metering (such as MIT and ground delay) when rerouting was not applied. Also, due to time and resource limitations it was not possible to model all the benefit mechanisms presented in Figure 5, Figure 7, and Figure 6. In particular the benefit mechanisms connected with dashed arrows (such as duration of rerouting application, varying the set of flights impacted, and accounting for FCA uncertainty) were not modeled. The current benefit assessment is therefore conservative as more benefit mechanisms may be modeled and analyzed.

Figure 8 shows the methodology for modeling and analyzing the improvement in rerouting around an FCA by using TFM R&D tools. The first and second benefit mechanisms described in this section are modeled together through the improvement in the rerouting by using an integrated TFM approach, combining rerouting and metering decisions. This represents only one example of integrated TFM. The collaborative rerouting benefit mechanism is also contained within the same approach, where airlines suggest alternative reroutes around the FCA. Each step in the flow diagram in Figure 8 is described below with the implementation details.

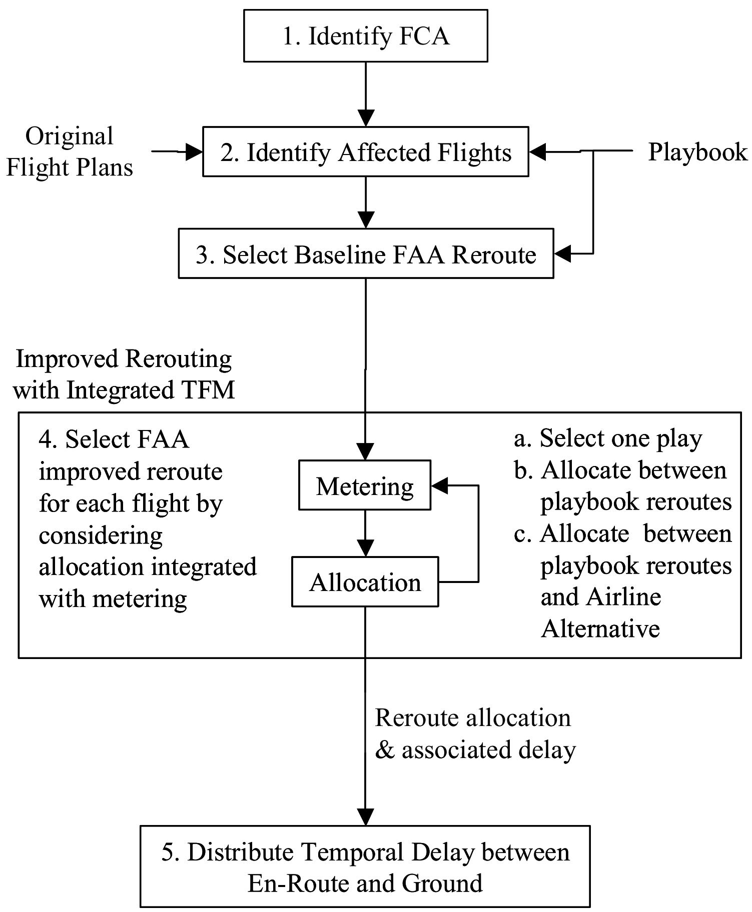
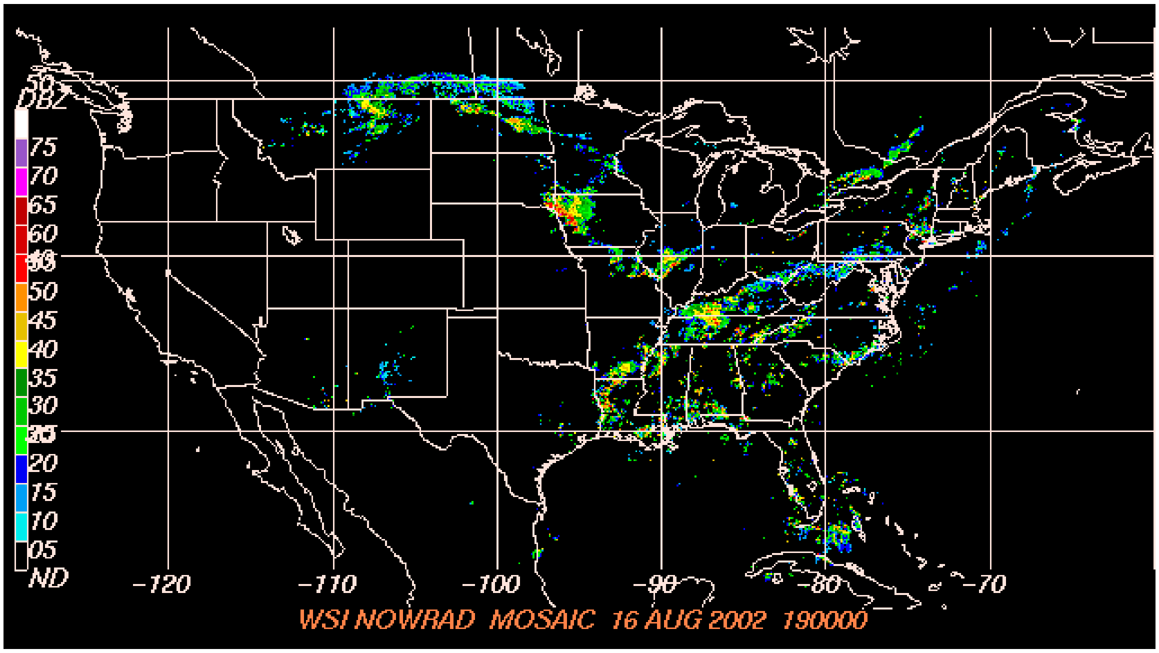


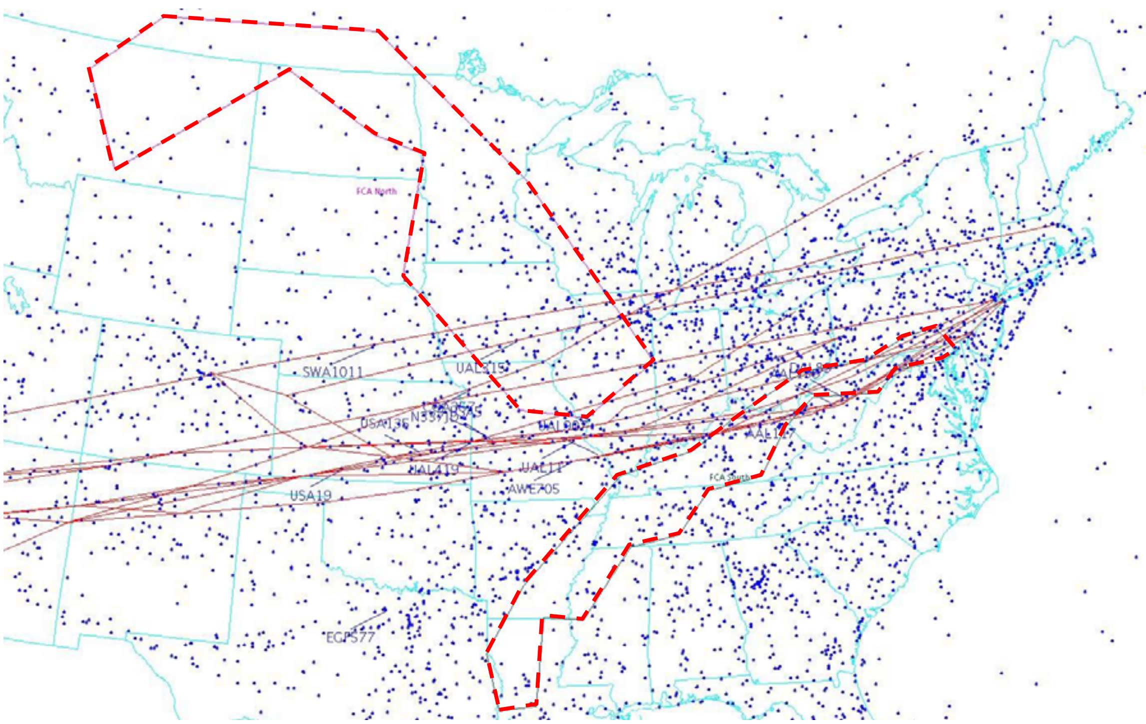
Figure 8. Methodology for modeling the benefit mechanisms of using SWEPT for improved rerouting around an FCA.

1. Identifying an FCA

The FCAs analyzed in this study were chosen from a number of days in which traffic data and Command Center logs were available. Through these logs it was possible to determine the TFM initiatives that were imposed by the Command Center in order to mitigate the effects of the FCA on each day, thus providing a baseline for the analysis. Figure 9 below shows one of the FCAs used in this study, as an example. The first part of the figure shows the weather that affected the NAS and the second part shows an FCA (in red polygons) surrounding the weather and a number of flight plans (in dark red) that the FCA was predicted to affect.



a)



b)

Figure 9. Weather and affected flights. a) shows the NEXRAD weather map for August 16, 2003. b) shows flight plans of a selection of the flights affected by the weather, as identified in FACET. The blue dots show aircraft positions at the time of image capture.

2. *Identifying Affected Flights:*

The flights directly affected by the FCA are the flights for which the original flight plan passes through a sector impacted by the FCA. Since this study analyzed FCAs that actually occurred on particular days, the affected flights were identified as the flights that were included in the reroutes that the Command Center imposed in response to the FCA on that day. These flights were identified by applying and simulating the reroutes in FACET. FACET's logic for identifying these flights is believed to differ somewhat from the actual reroute application, since FACET's input (TRX files) does not distinguish between departure and through flights, while many reroutes distinguished between these two sets of flights. Therefore, some flights that FACET predicts to be rerouted may have not been rerouted in actuality. Such discrepancies between FACET's models and actual operations prevented the use of actual traffic data as a valid baseline.

The identified set of flights affected by an FCA was held constant throughout the simulations representing the different benefit mechanisms. In other words possible improvement in the Command Center decision as to which flights to reroute and delay was not analyzed due to time constraints.

3. *Selecting FAA Reroute Baseline:*

The reroute imposed by the Command Center in response to the FCA that occurred on each day was used as the baseline reroute. The Command Center often imposes a number of reroutes, typically selected from the playbook, and modified. Improvements to specific selected reroutes were then analyzed (as opposed to improvements to the combination of reroutes). The baseline reroute was simulated using FACET and then metered by keeping the load of the most congested sector along the reroute below its load capacity, as described in *Rerouting decision for each flight* below.

4. *Selecting Improved Rerouting Using Integrated TFM Approach*

In this model the benefits of using SWEPT to support rerouting aircraft around an FCA based on an integrated TFM approach are determined. In making the rerouting decision, this approach considers the reroute distance, the congestion on the reroute and the required temporal metering on the reroute.

Analysis scenarios

A number of analyses were conducted, capturing different benefit mechanisms:

a) Selecting one playbook reroute: In this analysis and the next, the Command Center simulates and compares different playbook reroutes, for the same set of flights and the same duration. The differences between the reroute alternatives include both the distance traveled and the associated congestion. In case a), one of the playbook reroutes is selected and all flights are rerouted along it.

b) Allocate between playbook reroutes: In case b), flights are allocated between alternative playbook reroutes on a flight by flight basis. The allocation decision is also based on both the distance traveled and the metering delay required due to congestion.

c) Allocating flights between playbook and airline alternative reroutes: This analysis models the effect of airline collaboration in rerouting. A customized (non playbook) reroute is selected to represent the airlines choice and flights are allocated between the playbook reroute selected by the Command Center and the airline's alternative, using the same approach as in case b).

Therefore, the main benefit mechanisms that were modeled and analyzed are shorter reroutes, a more balanced allocation of flights between multiple reroutes and integration of the rerouting decision with the metering resulting from associated congestion. These were analyzed both under FAA use of SWEPT to compare alternative reroutes and under collaboration with airlines.

Reroute alternatives selection

The alternative reroutes were selected by examining the FCA (severe weather) that existed on each day and its progress in time. Both actual NEXRAD plots and predicted plots, based on a NEXRAD web-based model, were used. Alternative reroutes were then selected, manually, such as the weather would be avoided safely (both actual and predicted) but such that the reroutes are shorter to the extent possible. Congested sectors were also avoided to the extent possible. These alternative reroutes pass closer to the FCA and attempt to minimize the flight time necessary to avoid the FCA. Alternative playbook reroutes representing Command Center alternatives and customized alternative reroutes representing airlines alternatives were selected and analyzed. For simplicity, the airline alternative was selected according to the same criteria as the playbook alternative reroute (namely shorter distances minimizing flight time while avoiding highly congested sectors). A higher fidelity model of the airlines preferences and selection criteria was considered beyond the scope of this task and may be considered in future work[6]. Figure 10 shows the alternatives to the CAN_1_EAST reroute implemented on June 11, 2003 in response to the weather shown by the red polygons. Two alternatives are shown: ECK which is another playbook, and an airline customized alternative.

Rerouting decision for each flight

The reroute alternatives were then simulated using FACET. The decision to select a reroute for each flight is based on the performance of the reroute taking the delay resulting from congestion and required temporal metering into account.

For case a.) where one alternative reroute is to be selected, all flights are simulated to be rerouted along each reroute alternative with the metering needed to mitigate the resulting congestion on the reroute. The metering is simulated by keeping the load of the most congested sector along the reroute below its load capacity. The most congested sector for all flights rerouted along the reroute alternative, is selected as follows: For each sector along the route, the sector loading over the duration of the playbook reroute was calculated in 5 minute intervals as the maximum number of flights in the sector in that 5 minute time period. The number of flights by which loading

[6] For example, integer-programming algorithms such as Bertsimas et al. and Nilim et al. [11, 12] may be used to select a different reroute for each flight based on minimizing deviation from the schedule and maintaining NAS sector capacity constraints.

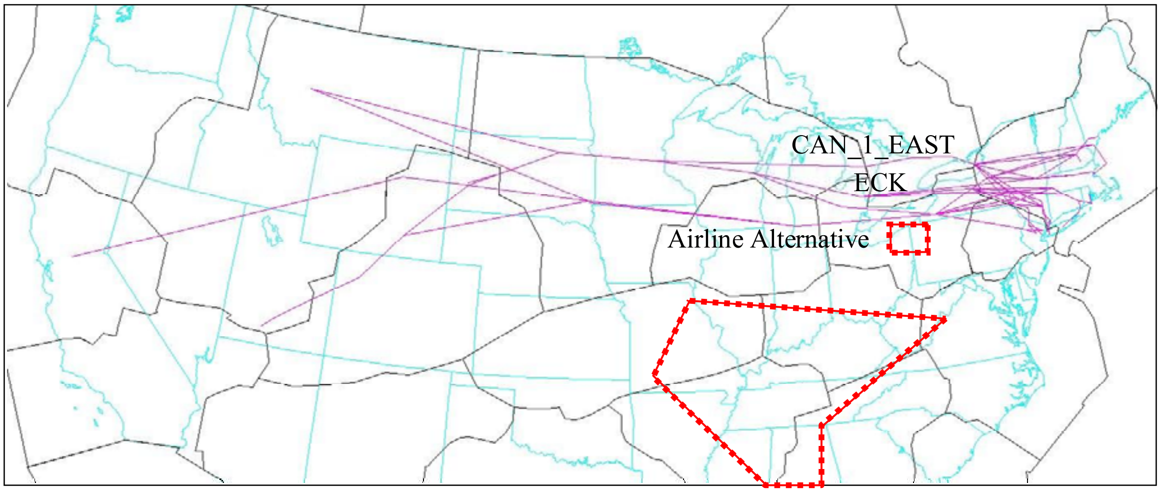


Figure 10. Alternative reroutes for a flight with original flight plan passing through the FCA indicated by the red dashed boxes. These boxes indicate the FCA for which the CAN_1_EAST playbook reroute was implemented on June 11, 2003.

exceeded capacity was then summed across all time intervals. This “integral of overload” was the measure used to determine the most congested sector. Choosing a single sector to represent congestion on each reroute is a simplification, as mitigation of congestion in this sector may not eliminate congestion in all sectors on the reroute.

The metering algorithm is time based and uses a model of a sector as a series of timeslots [6]. Each sector can hold a certain number of flights at a given time. This number of flights is equal to a given sector capacity. The MAP values were used to represent sector capacities as discussed in Section 3.1.2. Each flight requires access to certain sectors according to each reroute trajectory. The usage of sectors by a flight is characterized by an occupancy time. If a flight takes longer to traverse a sector than the duration of one timeslot, then it will need to be assigned to more than one timeslot, while traversing the sector. For example, if a flight takes 10 minutes to traverse a sector, it will occupy five 2 minute timeslots.

The metering algorithm assigns to these sector timeslots the rerouted flights and the flights that were originally planned to fly through these sectors. Flights are initially assigned according to their unmetered flight plans. However, when this causes sector timeslots to be loaded beyond the sector capacity, the flights are assigned on a first come first serve basis, and flights not assigned are delayed to the next available timeslot.

For allocating flights between multiple reroutes – playbook in case b) or customized in case c) – an allocation algorithm that integrates the metering with the rerouting is used. The allocation algorithm assigns each flight to the reroute alternative that minimizes total delay (combination of reroute delay and metering delay). This algorithm was implemented externally to FACET (in MATLAB).

The most congested sector along each reroute alternative is the same sector selected in case a), i.e. it is chosen by assuming that all flights are rerouted along the reroute alternative in question.

Having identified most congested sectors, the next step is to rank alternative routes for each flight according to undelayed ETA. This information comes from the FACET simulation of each reroute. For each flight, the reroute with lowest ETA is ranked number one. All other alternative reroutes are then assigned a delay threshold. Delay threshold is an indication of the total amount of delay that the flight would have to save, in order to switch from its number one ranked reroute to the alternative. Threshold delay is therefore the difference between the alternative reroute's ETA and the number one ranked reroute's ETA[7]. i.e. for alterative reroute *i*:

$$\textit{Threshold Delay}_i = ETA_i - ETA_{\#1\ ranked\ route}$$

The allocation algorithm then uses an iterative process to allocate flights to sector timeslots. Figure 11 below shows the order in which the sector timeslots are iterated. Sector timeslot 1 is allocated flights in iteration 1, sector timeslot 2 is allocated flights in iteration 2, and so on.

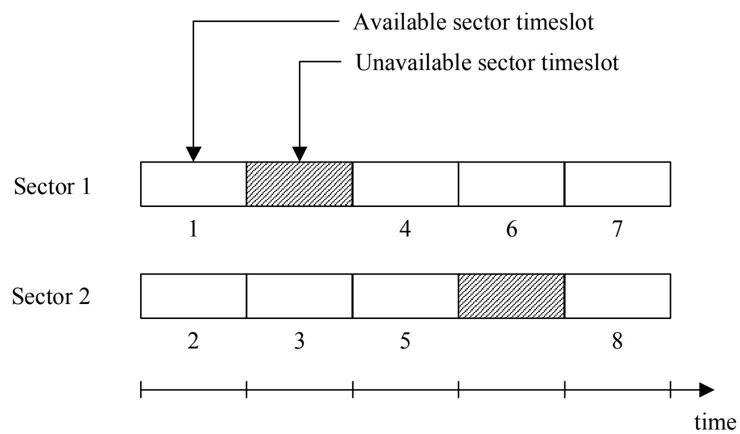


Figure 11. The allocation algorithm is iterative, and allocates flights to one sector timeslot at each iteration. The numbers in the figure above show at which iteration each sector timeslot is allocated flights.

This flight allocation algorithm follows an algorithm developed by Burke [6]. A preferred route is defined for each flight. This preferred route corresponds to the rerouted flight's number one ranked reroute alternative. This route will require access to particular sector timeslots (if it is to fly the route with no further delay). When this allocation causes sector timeslots to be loaded beyond the sector capacity, the flights are – as in the metering algorithm in case a) – assigned on a first come first serve basis, and flights not assigned are delayed to the next available timeslot. This is done by adding this incurred delay to the flight's ETA on that reroute alternative. If this delay is greater than the threshold delay of another alternative, the reroute ranking (based on the modified ETAs) for that flight will change for the next iteration, i.e. the reroute with its threshold delay exceeded will now become the number one and hence most preferred reroute, for that

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[7] Threshold delay can be a function of other factors in addition to ETA. If a route flies for a long period of time at low altitude, it will not be desirable even if its ETA is lower than the alternatives. Other factors, such as altitude, may be considered in the calculation of threshold delay in future work.

flight. The iteration process runs through all sector timeslots that are over capacity until none remain. In this way, the integrated reroute allocation and metering ensure that the sectors do not exceed capacity at any time.

5. Distribute temporal delay between en-route and ground

The allocation of flights to sector time slots, such that sector capacity is not exceeded, results in delays that need to be absorbed and propagated upstream. In operation these delays are absorbed and propagated upstream using temporal metering restrictions such as Miles In Trail, holding, Ground Delay, and Ground Stop. Since for most analysis scenarios modeled in this study the FCA is en-route, most en-route delays are absorbed at the same altitude. Therefore, the benefit of propagating the en-route delays upstream does not result in fuel burn savings since the upstream delays are absorbed at the same altitude. However, delays propagated to the departure airports are absorbed on the ground without any fuel burn. Therefore, for simplicity, only the distribution of the metering delay between en-route and ground is modeled.

A delay threshold, above which delay is absorbed on the ground, and not in the air, was identified for each flight simulated by comparing the amount of metering delay to be absorbed to an historical breakdown of delay absorbed in the air and on the ground for that level of total metering delay. This was completed according to an historical data analysis using the Aviation System Performance Metric (ASPM) database, as described in more detail in Section 7.2. The resulting breakdown of delay absorbed in the air and on the ground was applied to the delay results of the simulation, and the respective economic benefits of each component of the delay were calculated accordingly. The operating cost of delay absorbed on the ground does not include the fuel and oil costs of delay absorbed in the air.

5.3. Benefit Mechanisms and Modeling of Airspace Dynamic Resectorization

The benefit mechanisms of solving airspace design problems using SWEPT are detailed in the figure below:

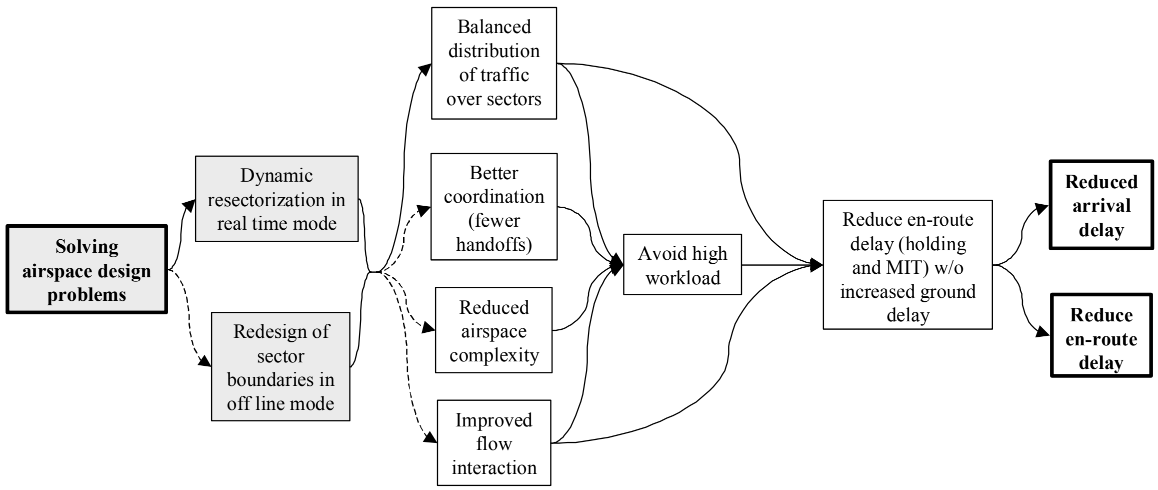


Figure 12. Benefit mechanisms of solving airspace design problems using SWEPT.

As described in Section 4, solving airspace design problems using SWEPT includes dynamic resectorization in a real time mode, and redesign of sector boundaries in an offline mode. The benefit mechanisms of these modes are described in detail below. As seen in Figure 12, and as discussed below, the benefit mechanisms of the two modes are similar except for the time scale of their effects.

Both dynamic resectorization (real time) and offline sector redesign result in a more balanced distribution of traffic over the sectors; improved coordination between controllers, as the sectors are redesigned to reduce the number of hand-offs required; reduced airspace complexity; and improved interaction between the traffic flows. Examples of resectorization that have some of these effects include separating two streams between two controllers; redesigning sector boundaries to avoid streams exiting and then re-entering a sector; and switching fixes such that flows do not intersect. Each of the benefit mechanisms described above results in avoidance of particularly high workload in the sectors in question, since sector overload is avoided. Avoidance of high workload results in a reduction in the need for en-route holding and MIT. This is because en-route holding and MIT are required to reduce the traffic flow through the sector when a sector is overloaded. By avoiding high workload, this requirement for en-route holding and MIT is reduced. En-route holding and MIT is also reduced directly by improved flow interaction and more balanced distribution of traffic. As discussed for the benefit mechanisms of rerouting around an FCA using SWEPT, this results in reduced en-route delay and reduced arrival delay since ground delay is not increased.

Due to time constraints only dynamic resectorization using SWEPT will be modeled in detail in this study.

5.3.1. Overview of Modeling Methodology

The modeling of dynamic resectorization using SWEPT involves modeling the dynamic resectorization in response to a congestion problem, and derivation of the benefits of dynamic resectorization by modeling the impact of the resectorization on the need for temporal restrictions to mitigate the congestion.

Taber et al [7] identified a number of scenarios where dynamic resectorization is used operationally. These are all scenarios in which limited resectorization is used to mitigate the effects of congestion. They include equipment outage, weather, special use airspace, airport configuration change, traffic volume and oceanic track change. In order to model a scenario that is operationally feasible, one of these listed scenarios was chosen for the modeling of dynamic resectorization. Since a weather problem is to be investigated in studying the benefits of SWEPT in rerouting around an FCA, the analysis would be simplified by using the same problem for analysis of resectorization. This allows significant parts of the model to be common with the FCA rerouting model, reducing the amount of modeling required. The weather problem presented in Section 5.2, represented by a corresponding FCA, was therefore chosen for analysis of using SWEPT for dynamic resectorization. The congestion that results from the FAA reroute is, however, addressed using resectorization instead of flight route allocation.

The methodology for modeling dynamic resectorization using SWEPT is presented in Figure 13, and is described in detail in the steps following.

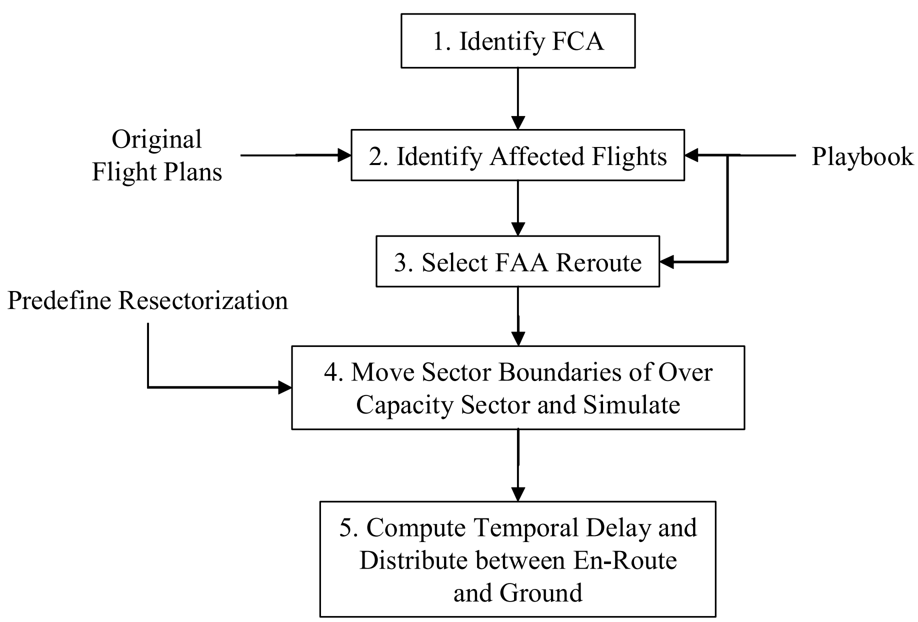


Figure 13. Modeling methodology for modeling of solving airspace design problems

1. Identify FCA

The FCA definition is the same FCA identified for using SWEPT for rerouting around an FCA, as described in Section 5.2.

2. Identify Affected Flights:

The identification of flights affected by the FCA is identical to the process described for rerouting around an FCA using SWEPT, as described in Section 5.2, where the affected flights were identified by FACET as those that were included in the reroutes that the Command Center imposed in response to the FCA simulated.

3. Select FAA Reroute:

The purpose of identifying and applying reroutes is to create the scenario described in Taber et al. [7] i.e. to create congestion resulting from an FCA. As for the baseline case for rerouting around an FCA using SWEPT, described in Section 5.2, the reroute selected for the simulation was the playbook reroute actually imposed by the Command Center in response to the FCA on each day simulated.

Sector loading and sector capacity were also calculated using FACET as described in Section 5.2, identifying which sectors are over capacity.

4. Move Sector Boundaries of Over Capacity Sector and Simulate:

Dynamic resectorization is dependent on the scenario under consideration. Most commonly resectorization is performed according a to predefined resectorization based on existing boundaries and automation [7]. Some of these predefined resectorizations are available in FACET. Unlimited resectorization, where sector boundaries are moved wherever required, and not according to any existing boundaries or predefined resectorization, is not expected to be enabled in the near future as existing automation does not support it. Thus, to the extent that predefined resectorization is available in FACET, sector boundaries were moved to coincide only with predefined resectorizations. Where no predefined resectorization was available, boundaries were moved wherever required, but avoiding significant jetways and merge points. ARTCC boundaries were not moved in any case.

In the simulation the resectorization of the sectors was based on mitigating the congestion resulting from the FCA and playbook reroutes simulated. Sector boundaries were moved to balance the sector loading between sectors that were over capacity, and sectors that were under capacity, as identified using FACET. Two example scenarios for such sector load balancing are presented in Figure 14 and Figure 15. Figure 14 shows a resectorization approach derived from Taber et al [7] that applies to a particular scenario where flights are rerouted into an adjacent sector to avoid an FCA.

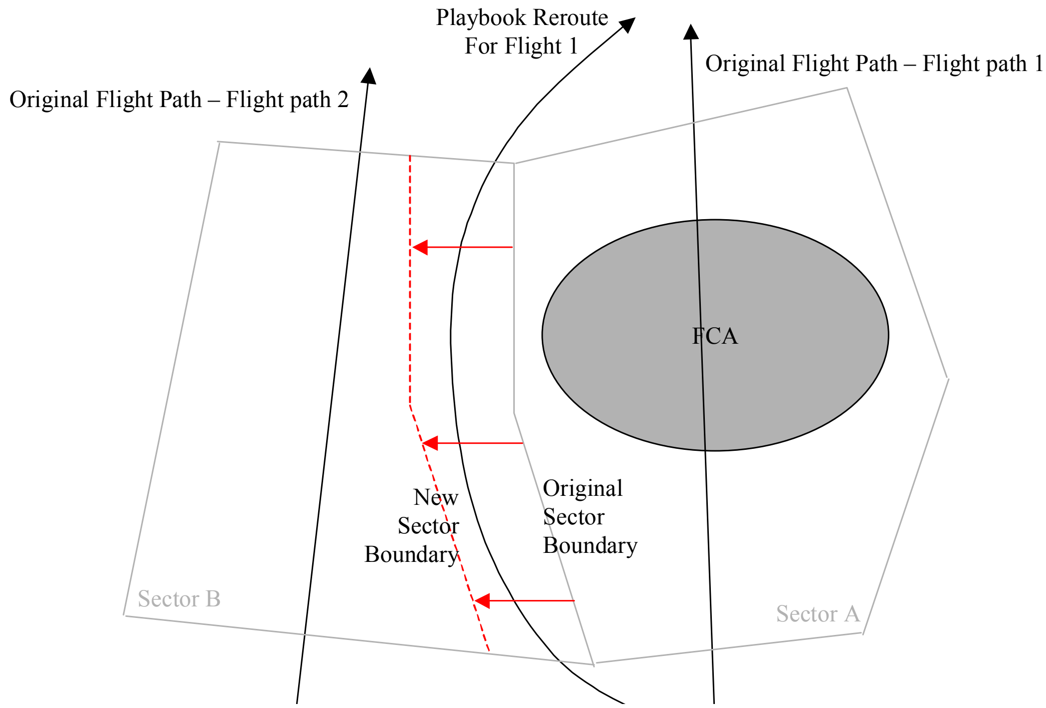


Figure 14. Sketch of how dynamic resectorization is used to alleviate congestion in sector B after sector A is blocked by an FCA, resulting in a global reroute of flights on flight path 1 through sector B.

In the hypothetical scenario presented in Figure 14, the FCA has blocked sector A, causing flights along flight path 1 to be rerouted to the playbook reroute, which passes through sector B. Since sector B has flights on flight path 2 as well, it becomes overloaded. Sector A, however, has low sector loading, because all flights in the sector have been rerouted elsewhere. The boundary between the sectors can be moved to keep the reroute in sector A. Sector A then handles all the traffic it would have handled had there been no FCA, and no extra burden is added to sector B.

Figure 15 shows another approach, also derived from Taber et al. [7], which may be applied to a wider variety of scenarios. In this approach resectorization is performed with respect to jet routes crossing a sector. Any sector with more than one parallel jet route can be resectorized in this way, should it be over capacity and the adjacent sectors be under capacity. The resectorization is completed by moving boundaries such that one or more jet routes are moved into the adjacent sectors. The predefined sectorization can be defined by the position of the jet routes.

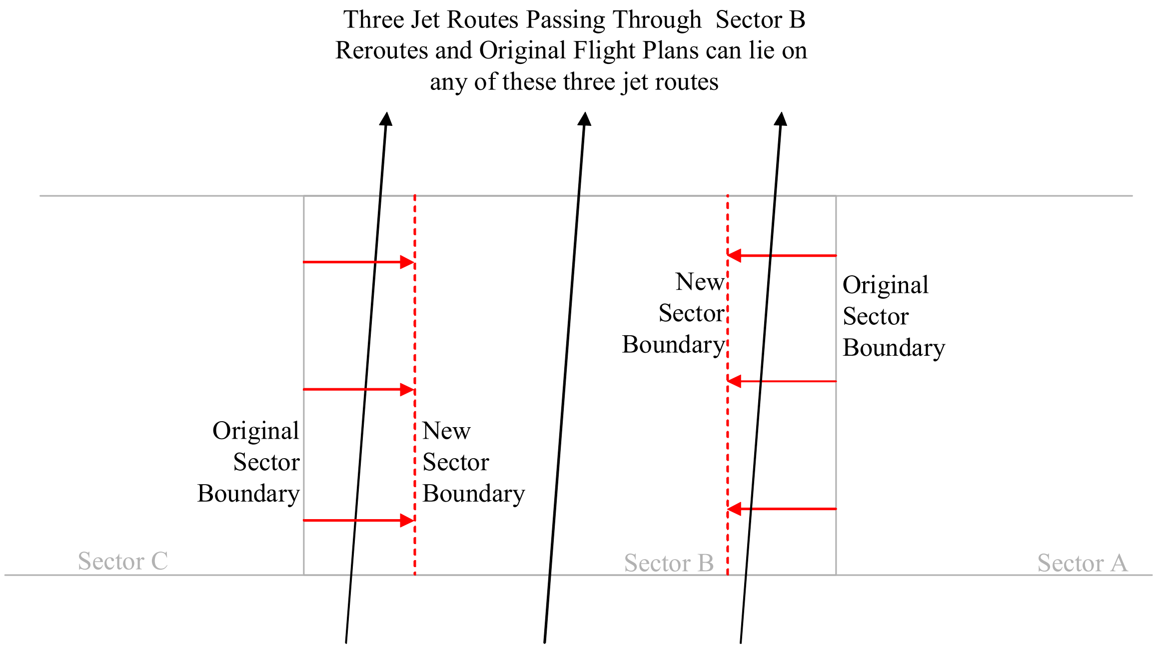


Figure 15. Another resectorization approach, for an overloaded sector through which more than one jet route passes.

Using common resectorization methods, the use of SWEPT for resectorization to resolve the congestion resulting from a reroute around an FCA was simulated. The performance of the system using SWEPT for resectorization can be compared to a baseline where resectorization was not applied, thus estimating the benefits of using SWEPT for resectorization, particularly in delay savings. The performance of the system as simulated can also be compared to a baseline where a less efficient resectorization was used without the help of SWEPT (for example, using a common resectorization that is not optimal under the congestion situation). However, this was not done due to time constraints.

5. Compute Temporal Delay and Distribute between En-route and Ground

As described in the resectorization benefit mechanisms in Figure 12, better resectorization using SWEPT should lead to a reduction in the need for TFM initiatives (such as MIT and Ground Delay Programs) to mitigate the effects of congestion and high workload, as for rerouting around an FCA using SWEPT, as described in Section 5.2. This benefit mechanism is thus modeled in the same way as described in Section 5.2. Flights are allocated to sector time slots such that sector capacity (after resectorization) is not exceeded, resulting in delays that need to be absorbed and propagated upstream. In operation these delays are absorbed and propagated upstream using temporal metering restrictions such as Miles In Trail, holding, Ground Delay, and Ground Stop. As for rerouting around an FCA using SWEPT, described in Section 5.2, only the distribution of the metering delay between en-route and ground is modeled. Details are presented described in Section 5.2.

5.4. *Benefit Mechanisms and Modeling of Preemptive Airline Collaboration*

As described in Section 3, the airline response to congestion that will be modeled in this study is restricted to real time planning responses by airline dispatchers using FACET-AOC and does not include long-term responses such as schedule changes according to offline historical data analysis using FACET-AOC. This is because, according to NASA's feedback, FACET-AOC is not currently expected to include decision aiding tools for higher level schedule redesign. In particular the function that is analyzed in this study is enabling preemptive actions by the airlines in response to a NAS constraint, by FACET-AOC, prior to any FAA TFM initiatives to deal with the constraint.

The benefit mechanisms of the enabling of preemptive airline response to NAS constraints, using FACET-AOC, are presented in Figure 16 below.

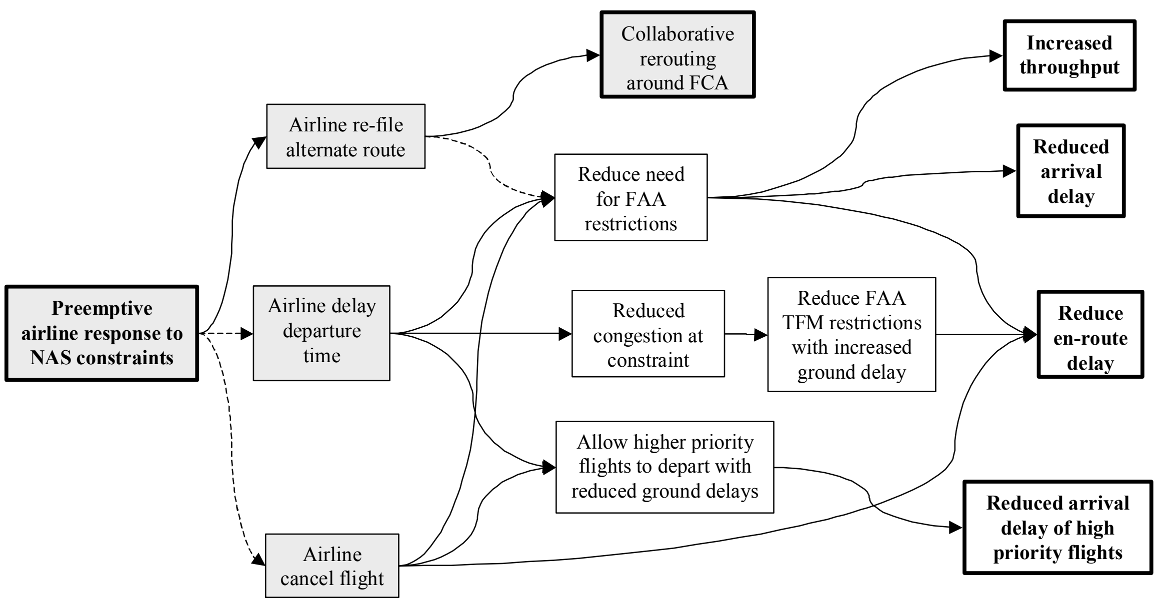


Figure 16. Benefit mechanisms of the enabling of preemptive airline response to NAS constraints, using FACET-AOC.

Three main airline actions in response to NAS constraints are the re-filing of an aircraft's flight plan on an alternate route; the delay of a departure by the airline; and the cancellation of a flight by the airline. Using FACET-AOC, each of these actions can be applied, according to the airline's own priorities, avoiding or reducing the effects of an FAA TFM initiative resulting from the constraint. Each of these actions can be completed independently or in conjunction with each other. The benefit mechanisms presented apply to independent completion of the actions (e.g. a reroute applied without any change in departure time). A combination of these independent benefits results if the actions are completed in conjunction.

The re-filing of an alternate route by the airline, even if performed preemptively, represents an aspect of collaboration between the FAA and the airlines in the rerouting decision. Therefore, the collaborative rerouting benefit mechanisms described in Figure 7 are enhanced by the airline preemptive rerouting action.

All three preemptive actions by the airlines (re-filing a route, departure delay, and flight cancellation) would result in less traffic being impacted by the constraint, and thus less congestion at the constraint. This would require less severe TFM initiatives to be put in place by the FAA to deal with the constraint. This may include, for example, reduced en-route holding, reduced MIT restrictions, and less need for a playbook reroute to be applied. As described in Section 5.2 a reduction in restrictions would result in a reduction in en-route delay and arrival delays. These reductions benefit all traffic and not just the flights that were acted upon by the airlines. A reduction in restrictions also results in an increase in system throughput as demand pressure is maintained at destination airports.

The delay of a departure by the airlines can result in a reduction in the congestion at the constraint. The result of this is reduced en-route delay for the aircraft as it may encounter less severe TFM metering restrictions by the FAA. Although en-route delay is reduced, ground delay may be increased, and arrival delay is thus not necessarily decreased.

The delay of a departure and canceling a flight by the airlines can result in the reduced departure delay of a higher priority flight, for example, if two aircraft departure slots are swapped. Although the delayed aircraft may incur higher delays than otherwise, the arrival delay of the higher priority flights is reduced. This may have many benefits including avoiding missed connections and further cancellations, as well as other benefits, depending on the priorities of the airline, as discussed in greater detail in Section 7 on economic benefits.

Cancellation of a flight by the airlines does not reduce arrival delay, as the flight is cancelled, but operating costs that would have been incurred by the flight are reduced. The en-route delay can thus be considered to also have been reduced.

5.4.1. Overview of Modeling Methodology

The benefits of preemptive airline response to NAS constraints, using FACET-AOC, can be estimated by modeling various scenarios. In order to simplify the analysis, the same scenario used to model the FAA's response to an FCA using SWEPT, in Section 5.2, will be used with the addition of preemptive rerouting by the airlines using FACET-AOC. The other preemptive actions such as modifying departure time and flight cancellation are not considered in this analysis and may be considered in future work.

Adding the preemptive airline action is achieved by introducing airline responses to the FCA prior to the FAA's TFM initiative (i.e. a playbook reroute). The rest of the model is identical to the baseline case of a playbook reroute followed by required metering. The modeling process is described below as a series of steps and is illustrated in Figure 17.

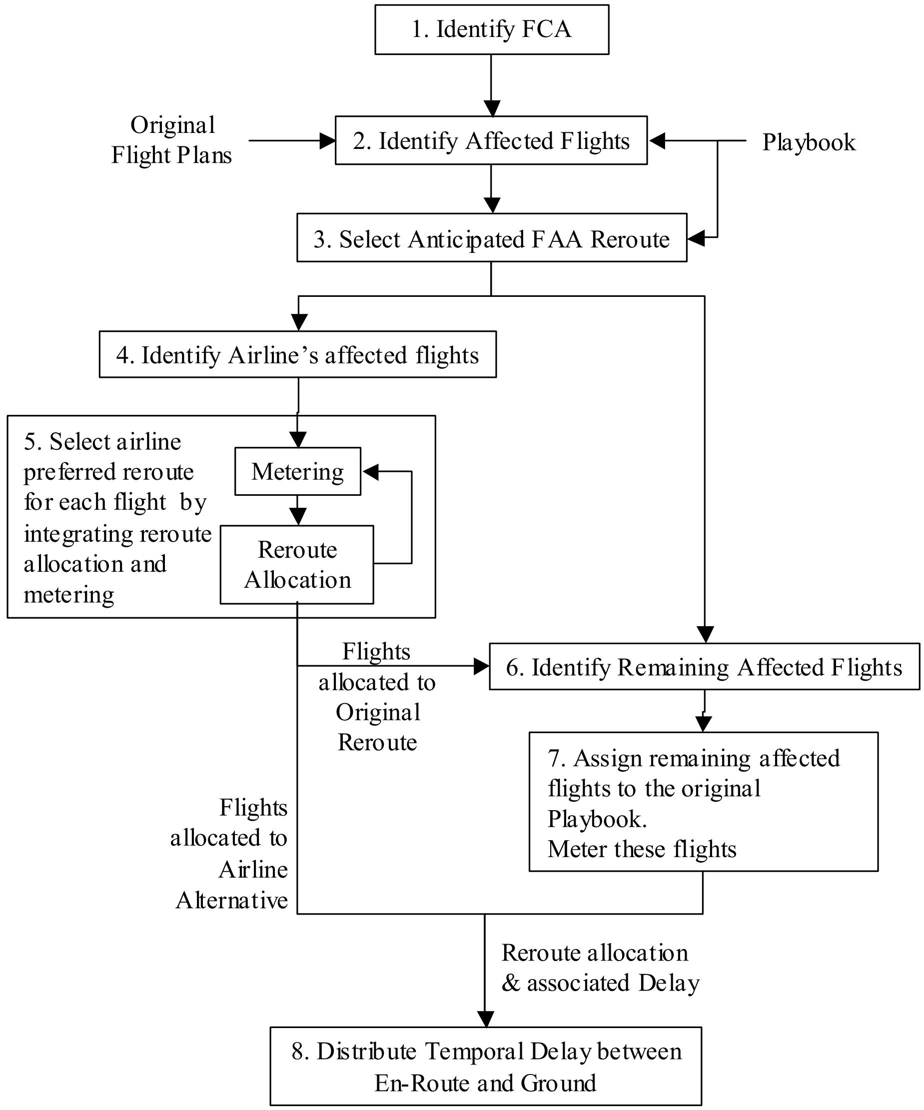


Figure 17. Modeling methodology for preemptive airline collaboration

1. Identifying an FCA

The FCA selection is the same as when using SWEPT for rerouting around an FCA, as described in Section 5.2.

2. Identify Affected Flights

The initial identification of all flights affected by the FCA is identical to the process for rerouting around an FCA using SWEPT, as described in Section 5.2. where the affected flights were identified by FACET as those that were included in the reroutes that the Command Center imposed in response to the FCA simulated.

3. Select Anticipated FAA Reroute

At this stage in the analysis the airline with FACET-AOC would anticipate the FAA's response to the FCA. The anticipated FAA reroute is the same reroute identified in Section 5.2. i.e. the playbook actually imposed by the command center in response to the FCA on each day simulated.

4. Identify Airline's Affected Flights

Following identification of the flights affected by the FCA, the flights affected by the airlines with FACET-AOC can be identified. Two cases are analyzed. In the first, just one airline is assumed to have FACET-AOC. The airline is chosen as the airline with the most number of rerouted flights. This airline's flights in the set of affected flights is then taken as those upon which preemptive action will be applied. The second case assumed that all airlines have FACET-AOC, and so all affected flights are chosen to be part of the set upon which preemptive action will be applied.

5. Select Airline Alternative Reroute

The airline alternative reroute is chosen in the same way as the airline alternative chosen for collaboration purposes in Section 5.2. i.e. the airline alternative reroute is chosen to minimize reroute distance and congestion while avoiding both the real and forecast weather. The result is the same airline alternative reroute for each example as was identified in Section 5.2.

Once selected, the airline will allocate flights between the anticipated playbook reroute and the airline alternative according to the same allocation algorithm introduced in Section 5.2. Metering is integrated in the allocation algorithm, meaning that the allocation between airline alternative and anticipated reroute includes TFM integration. The airline is however only allocating a small fraction of all flights selected to be rerouted. All flights not belonging to the airline are assumed to fly the anticipated reroute, and so contribute to congestion on that reroute, but not on the airline's alternative reroute. The allocation, as per the algorithm discussed in Section 5.2, is allocated flights based on minimizing metered ETA.

Following flight allocation by the airlines with FACET-AOC, the airlines would refile the flight plans for those allocated the airline alternative route. The FAA would accept or reject these modified flight plans. For the purposes of this study, it is assumed that all re-filed flight plans are accepted.

6. Identify Remaining Affected Flights

Following the preemptive allocation of flights between the anticipated playbook and the airline alternative by the airlines, the FAA is still required to respond to the FCA, as some flights still have flight plans affected by it. In real operations this may occur well after the flight plans are re-filed, as the FCA may only appear after the flights have taken off. The FAA response to the FCA will be modeled as the baseline – i.e. implementation of the original playbook reroute, and associated metering. No allocation between playbook alternatives will be performed, so as to isolate the benefits of FACET-AOC from those of SWEPT. Thus the FAA are assumed to not have SWEPT. The first step for the FAA is then to identify affected flights. This will be a subset of the originally identified set of affected flights, as some flights have been reassigned by the airlines onto an alternative route that is not affected by the weather. This identification is modeled by removing the flights that have been allocated the airline alternative reroute in step 5 from the original list of affected flights. The new list of affected flights may therefore still contain some flights that belong to the airline with FACET-AOC.

7. Select Alternative Playbook

Following identification of the set of flights to be affected by the FAA reroute, these flights are assigned to the reroute, and metered according to the algorithm described in Section 5.2.4 step 4.

The FAA response to the FCA is thus affected by the preemptive action in that a smaller set of flights is rerouted. Another possible effect of preemptive action is a more severe impact on the FAA's response to the FCA. Such a response might be less need for a playbook reroute to be applied at all. These effects are not considered in this analysis, but may be considered in future work.

8. Distribute temporal delay between en-route and ground

The modeling of distribution of resulting delay between en-route and ground delay is identical to that discussed in Section 5.2.4 step 5.

6. TFM R&D Technical Performance Benefits

The technical performance for the three cases analyzed in this study, rerouting around an FCA, airspace dynamic resectorization, and airline preemptive response to an FCA, are presented in this section, in this order.

6.1. *Rerouting around FCA*

The results following have been calculated for a number of simulated playbook reroutes. The first three playbook reroutes are trans-cons, while the fourth and fifth are airport closures. The first playbook reroute is the CAN_1_EAST playbook reroute applied by the Command Center between 15:30 and 22:00 Zulu time on June 11, 2003[8]. The second playbook reroute analyzed is VUZ, which was applied by the Command Center between 14:32 and 23:00 Zulu time on September 15, 2002. The weather was such that no alternative routes were found until 18:00 Zulu time, so this reroute was analyzed between 18:00 and 23:00. The third reroute analyzed is FAM, which was applied by the Command Center between 18:00 and 22:00 Zulu time on August 16, 2002. The fourth playbook reroute analyzed is IAH_EAST applied by the Command Center between 13:41 and 00:00 on August 16, 2002. Weather was such that alternative reroutes were only found between 14:00 and 20:00. This playbook reroute was thus only analyzed between these times. The fifth playbook reroute was DFW_EAST, applied by the Command Center between 11:00 and 02:00 on September 19, 2002. This playbook reroute was analyzed between 14:00 and 00:00.

The delay numbers presented below are total delay caused by the reroute. This delay includes that incurred by rerouted flights as well as that incurred by other flights impacted by the reroutes – in particular in the sectors identified as most congested. This delay can be broken down into reroute delay (caused by the difference in distance between the chosen reroute and the original route for rerouted flights) and metering delay (the additional delay resulting from the metering of all flights, implemented so as to maintain sector loading within capacity), as described in Section 5.2. The performance of the baseline and of each improvement scenario are presented below.

6.1.1. Baseline

The baseline comprises a simulation of the playbook reroute, which was applied by the Command Center in response to severe weather. The total delays and their breakdown into reroute (distance) and metering (temporal) delays are shown in Table 1 below for all five reroutes analyzed. These numbers resulted from a simulation of each playbook reroute in FACET without metering and then simulating metering using the delay measuring technique developed in this study, as described in Section 5.2. The most

[8] When run, the modifications to the playbook reroute by the Command Center were not known, so this example does not include these modifications, but is the CAN_1_EAST playbook reroute as quoted in the National Playbook. All other reroutes include the modifications made by the Command Center.

congested resources identified for metering according to the method described in Section 5.2 are as follows:

CAN_1_EAST on June 11, 2003:	ZMP12
VUZ on September 15, 2002:	ZFW82
FAM on August 16, 2002:	ZID91
IAH_EAST on August 16, 2002:	ZFW42
DFW_EAST on September 19, 2002:	ZKC47

Table 1. Delay Statistics for the Baseline Playbook Reroutes

Playbook	Date	# of Flights Rerouted	# of Flights Metered[9]	Total Delay [min]	Reroute Delay [min][10]	Metering Delay [min][11]
CAN_1_EAST	June 11, 2003	103	240	1269	669	600
VUZ	Sept 15, 2002	57	193	2039	1825	214
FAM	Aug 16, 2002	46	291	573	469	104
IAH_EAST	Aug 16, 2002	83	295	2355	2144	211
DFW_EAST	Sept 19, 2002	369	632	7405	7375	30

Figure 18 below shows the demand, throughput and metering delay on August 16, 2002 for ZFW42 in the time period over which the IAH_EAST reroute was analyzed. All three metrics are measured with a time window of one hour. It is clear from the figure that the metering delay starts ramping up when the demand for the congested sector exceeds its throughput.

[9] This number is the total number of flights affected by the reroute congestion including both rerouted flights and all other flights passing through the most congested sector.

[10] Incurred by the # of flights rerouted.

[11] Incurred by the # of flights metered.

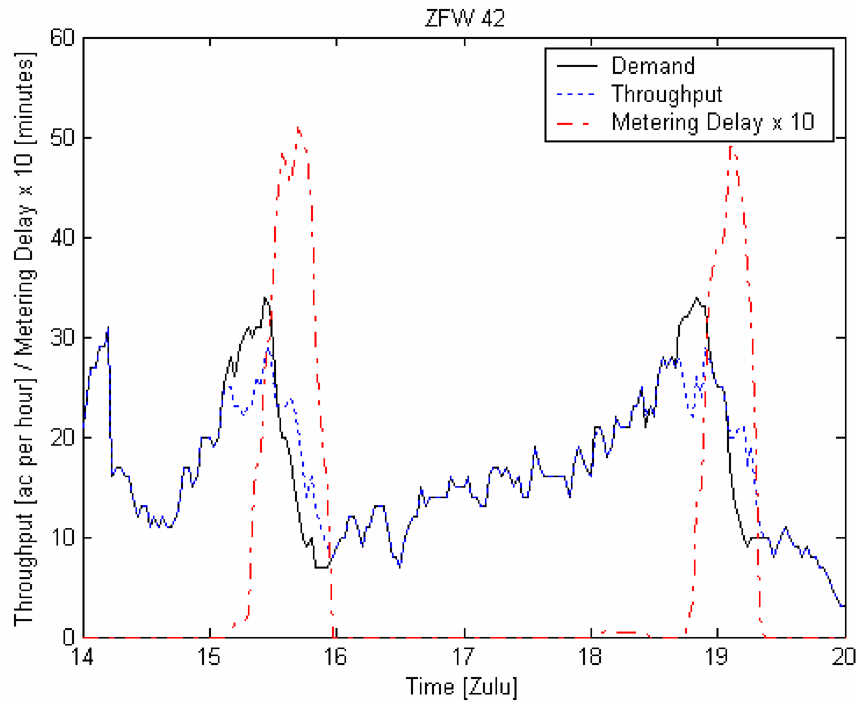


Figure 18. Throughput and Delay results for sector ZFW42 on the IAH_EAST reroute, August 16, 2002.

Figure 19 shows the loading versus capacity in ZFW42 as a result of direct simulation of the IAH_EAST playbook reroute in FACET without metering. Also shown in the figure is the loading after having been reduced by metering using the MATLAB program. It is clear from the figure that the sector loading was maintained below capacity. Metering is needed between 15:20 and 15:40 and between 18:52 and 19:04. This correlates well with Figure 18 above which shows metering delay deviating from zero between 15:00 and 16:00 and around 19:00.

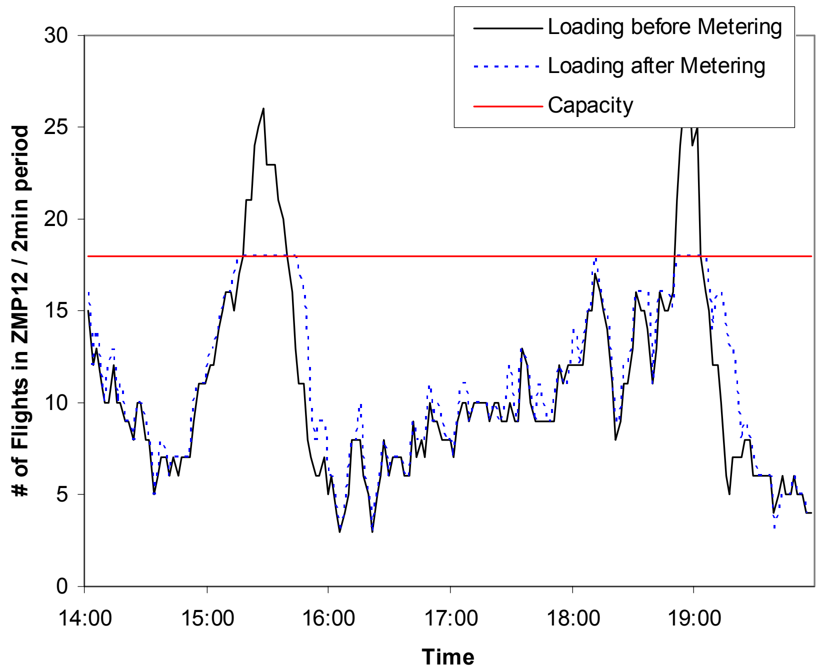


Figure 19. Loading before and after metering versus time of ZFW42 on August 16, 2002 with the IAH_EAST playbook reroute in place.

6.1.2. Improved Rerouting using Integrated TFM

This section comprises the results of improving the rerouting of flights by giving the FAA the ability to simulate an alternative reroute in FACET. This reroute is either an alternative playbook, or a suggested reroute coming from the airlines. The decision of how to reroute flights is made based on reducing reroute flight time integrated with an estimate of required metering resulting from the reroute choice. This integration follows the algorithm discussed in Section 5.2

In all results presented below, the benefit with respect to the baseline is identified. This benefit is quoted in total delay savings in minutes.

In the first two cases listed in Section 5.2.4 step 4, the FAA uses FACET to simulate alternative playbook reroutes in addition to the playbook reroute chosen. For the days analyzed, only one alternative was considered. The alternative reroutes and associated most congested sectors chosen based on the procedure described in Section 5.2 are as follows:

CAN_1_EAST on June 11, 2003:	ECK	ZOB37
VUZ on September 15, 2002:	VHP	ZKC41
FAM on August 16, 2002:	BUM	ZKC31
IAH_EAST on August 16, 2002:	See Figure 23 below	ZFW48
DFW_EAST on September 19, 2002:	See Figure 24 below	ZFW48

The alternative reroutes chosen for the two airport closure reroutes did not follow specific playbook reroutes from the National Playbook, but they were based on playbook reroutes from the National Playbook. Figure 20 to Figure 24 show the playbook reroutes and associated alternatives for the cases of CAN_1_EAST on June 11, 2003, VUZ on September 15, 2002, FAM on August 16, 2002, IAH_EAST on August 16, 2002 and DFW_EAST on September 19, 2002 respectively. Weather is shown as red dashed polygons. These polygons represent the position of the weather over the reroute period analyzed. The alternative routes chosen avoid the weather for the whole period analyzed in each case.

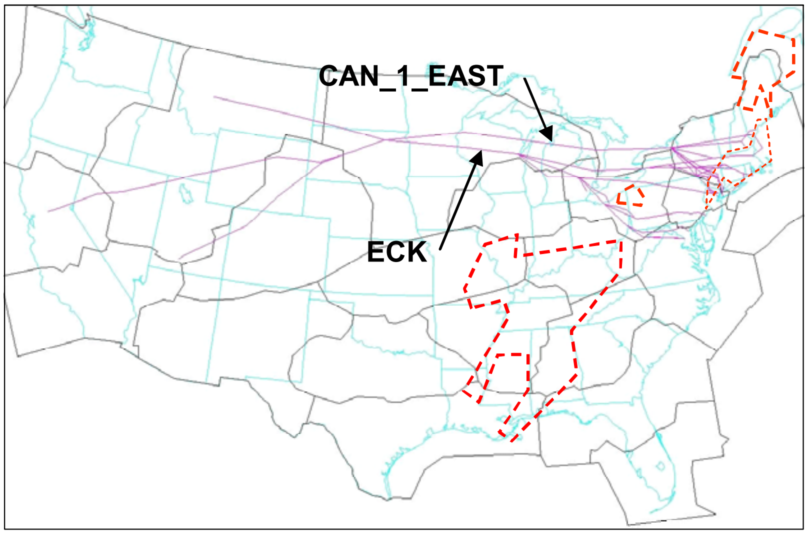


Figure 20. Map showing playbook reroute CAN_1_EAST on June 11, 2003 and alternative playbook reroute ECK.

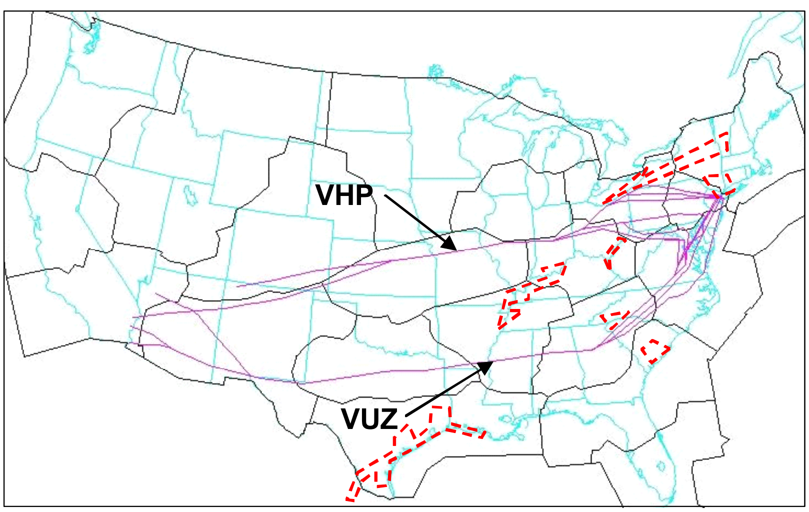


Figure 21. Map showing playbook reroute VUZ on September 15, 2002 and alternative playbook reroute VHP.

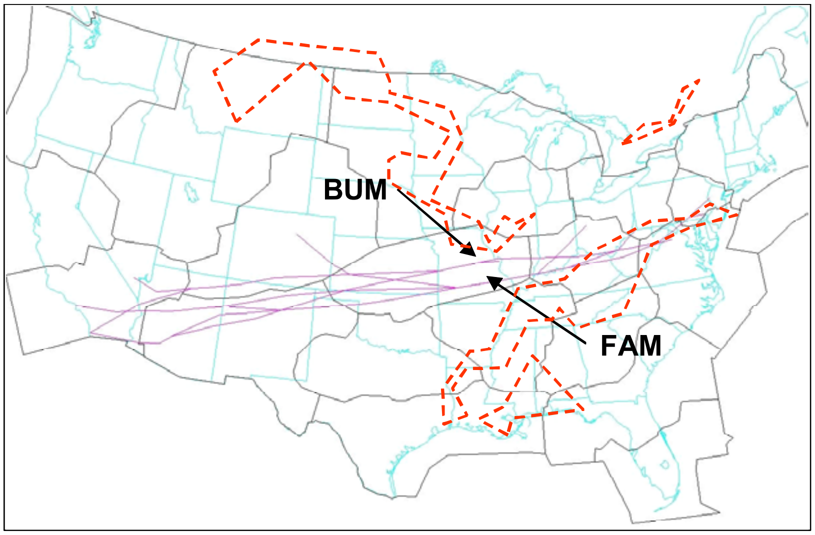
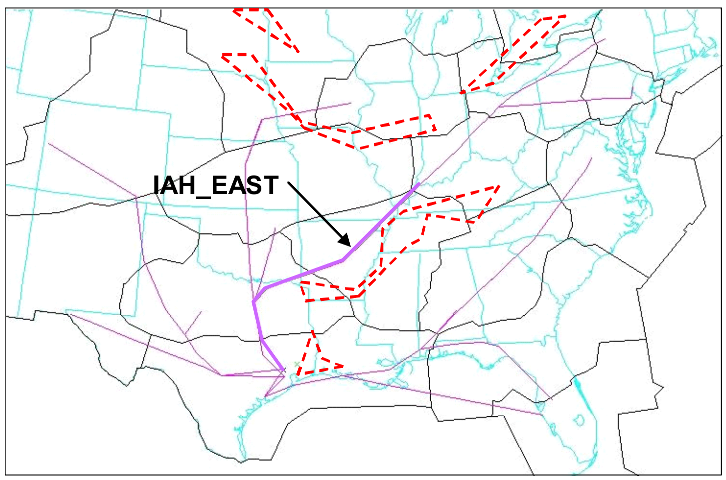
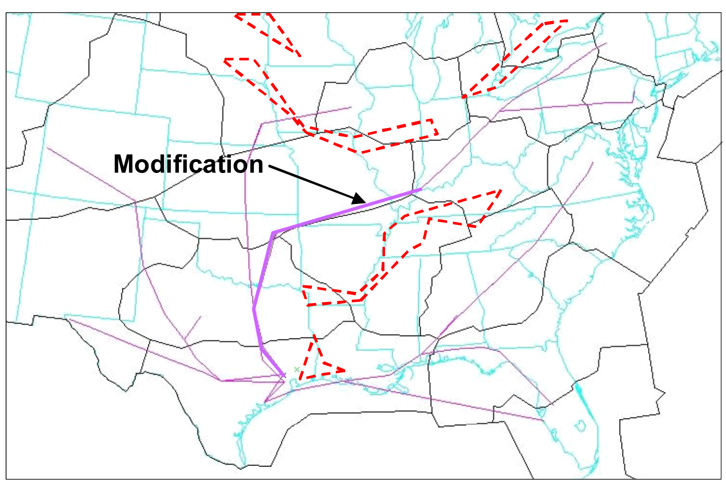


Figure 22. Map showing playbook reroute FAM on August 16, 2002 and alternative playbook reroute BUM.

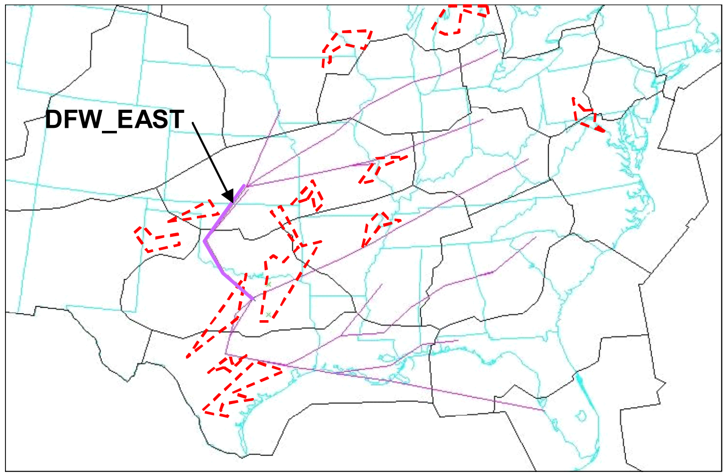


(a)

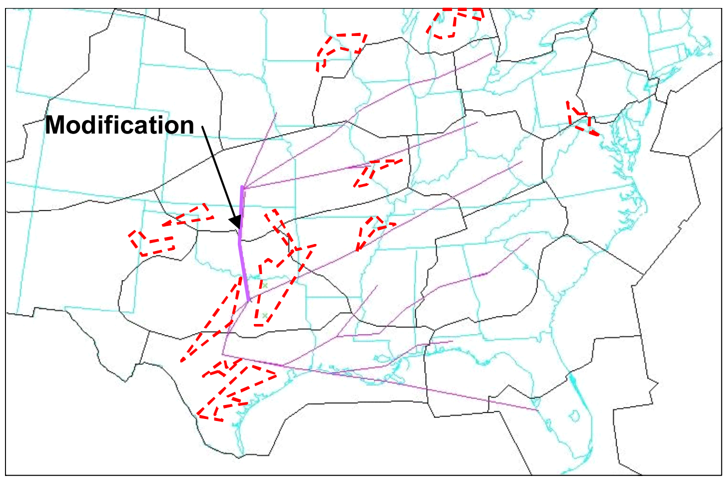


(b)

Figure 23. Maps showing (a) playbook reroute IAH_EAST on August 16, 2002 and (b) alternative reroute derived from other playbook reroutes



(a)



(b)

Figure 24. Maps showing (a) playbook reroute DFW_EAST on September 19, 2002 and (b) alternative reroute derived from other playbook reroutes.

a) Select One Playbook Reroute

In the first case, SWEPT is used to select one playbook reroute from the alternatives. All flights are sent on one playbook reroute. There is therefore no allocation. Table 2 shows the decision and resulting benefit for each playbook reroute analyzed. The decision of which reroute to choose is based on the total delay, i.e. the sum of reroute delay and metering delay (integrated approach).

Table 2. FAA Selection of one playbook reroute and delay statistics

Date	Reroute	# of Flts Rerouted	# of Flts Metered	Reroute Delay [min]	Metering Delay [min]	Total Delay [min]	Chosen Reroute	Delay Saving over Baseline [min]
June 11, 2003	CAN_1_EAST	103	240	669	600	1269	ECK	**188**
	ECK	103	372	1011	70	1081		
Sept 15, 2002	VUZ	57	193	1825	214	2039	VHP	**1937**
	VHP	57	202	-3	105	102		
Aug 16, 2002	FAM	46	291	469	104	573	BUM	**187**
	BUM	46	190	340	46	386		
Aug 16, 2002	IAH_EAST	83	295	2144	211	2355	Mod	**389**
	Modification	83	290	1867	99	1966		
Sept 19, 2002	DFW_EAST	369	632	7375	30	7405	Mod	**1557**
	Modification	369	715	5785	63	5848		

In the case of CAN_1_EAST on June 11, 2003, the reroute delay of the alternative is greater than that of the original playbook reroute. However, once metering has been included, the total delay is lower on the reroute. This shows the benefit of considering the metering when making the reroute decision. The resulting delay saving of using the alternative reroute ECK instead of CAN_1_EAST is 188 minutes.

Figure 25 and Figure 26 below show the throughput and delay for most congested sectors ZMP12 on CAN_1_EAST and ZOB37 on ECK on June 11, 2003, for the case in which all flights are rerouted along CAN_1_EAST and ECK respectively.

These figures show that ECK (indicated by ZOB37) is notably less congested than CAN_1_EAST (indicated by ZMP12) when all rerouted flights are on the reroute in question. This reduction in congestion and hence metering delay leads to a smaller total delay for the ECK alternative reroute. This is in agreement with the lower metering delay of 70min for the ECK playbook reroute relative to the 600min on the CAN_1_EAST playbook reroute (see Table 2).

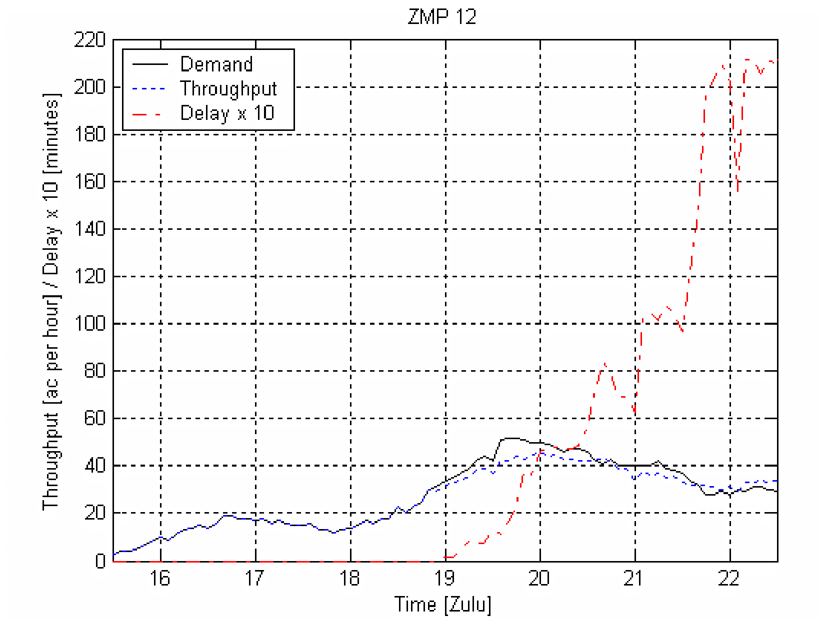


Figure 25. Throughput and Delay results for ZMP12 on the CAN_1_EAST playbook reroute, June 11, 2003 with all rerouted flights on this playbook reroute.

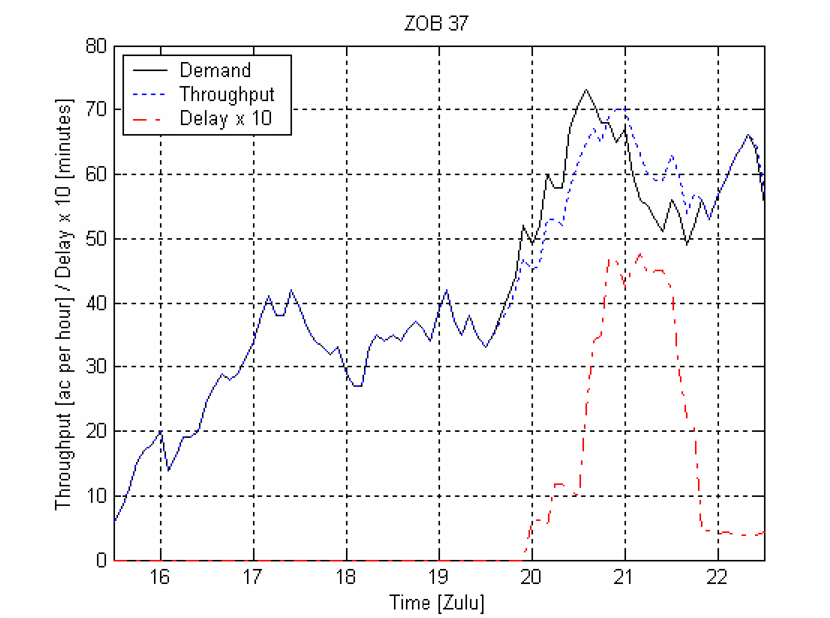


Figure 26. Throughput and Delay results for ZOB37 on the ECK playbook reroute, June 11, 2003 with all rerouted flights moved to this alternative reroute.

In the case of the VUZ reroute on September 15, 2002, the alternative reroute considered, VHP, is significantly better than the original playbook reroute. In fact, reroute delay is negative, meaning that this reroute is shorter than the original flight plans, when all are summed together. The result is a large saving of 1937 minutes. In the case of the FAM reroute on August 16, 2002 however, the alternative reroute BUM, although still shorter, is not so much so that the benefit is large. This reroute only results in a delay saving of 187 minutes. These 2nd and 3rd trans-con reroutes are examples of two extreme situations where SWEPT may be used. In the case of VUZ, there was great room for improvement of the playbook reroute chosen. In the case of FAM however, the reroute alternative was only slightly better.

b) Allocate to Playbook Reroutes

In the second case, the MATLAB allocation program developed is used in conjunction with the FACET simulations to allocate individual flights to either the original playbook reroute, or the alternative. The results are shown below. Baseline results are included for comparison purposes[12].

Table 3. Delay Statistics for allocation between the original playbook reroute and a playbook reroute alternative.

Scenario	Alt. Plbk	# of Flts Rerouted	# of Flts on Original	# of Flts on Alt.	# of Flts Metered[13]	Total Delay [min]	Reroute Delay [min]	Metering Delay [min]	Delay Saving [min]
VUZ Reroute on September 15, 2002									
Baseline	-	57	57	-	193	2039	1825	214	**-**
Allocation	VHP	57	0	57	338	102	-3	105	**1937**
FAM Reroute on August 16, 2002									
Baseline	-	46	46	-	291	573	469	104	**-**
Allocation	BUM	46	21	25	435	377	337	40	**196**
IAH_EAST Reroute on August 16, 2002									
Baseline	-	83	83	-	295	2355	2144	211	**-**
Allocation	Mod	83	67	16	502	1637	1522	115	**718**
DFW_EAST Reroute on September 19, 2002									
Baseline	-	369	369	-	632	7405	7375	30	**-**
Allocation	Mod	369	235	134	978	5816	5785	31	**1589**

[12] Note that the CAN_1_EAST playbook reroute on June 11, 2003 is not taken further in the analysis of choosing between playbook reroutes. Allocation could not correctly be performed on this data as the alternative reroute ECK also passes through the most congested sector chosen to represent CAN_1_EAST. The program written in MATLAB is not able to handle such a situation. This is a shortcoming of allocating based on a single sector on each reroute, which may be improved in future work.

[13] The number of flights metered differs in the baseline and allocation scenarios by the number of flights passing through the most congested sector on the alternative playbook route that are not rerouted flights. These flights are metered in the allocation case because this sector is metered. In the baseline, this sector was not metered.

The delay saving in the case of the VUZ playbook reroute on September 15, 2002 is significantly higher than – by an order of magnitude – that in the case of the FAM playbook reroute on August 16, 2002. This reiterates the observation that these two trans-con reroutes represent extremes where there is a lot of room for improvement by using SWEPT in the case of the VUZ reroute, yet not much that can be done in the case of the FAM reroute. It is also evident that all flights were allocated to the alternative VHP playbook reroute. This result is therefore the same numerically as the choice in Table 2 to fly everyone on the alternative VHP. The delay savings of the DFW_EAST airport closure reroute are also high, although this is to a large extent due to the large number of flights that this reroute affects.

Figure 27 below shows demand, throughput and delay on August 16, 2002 for ZFW42 after the flights have been allocated according to Table 3. Figure 28 shows demand, throughput and delay for ZFW48, which is the most congested sector identified on the playbook modification.

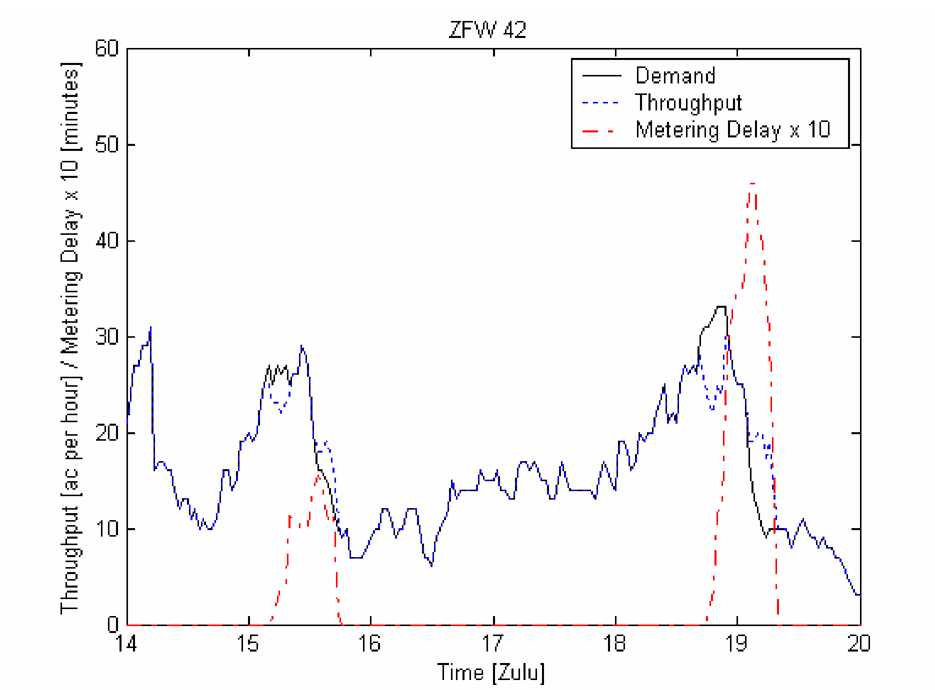


Figure 27. Throughput and Delay results for ZFW42 on the IAH_EAST reroute, August 16, 2002 after allocation of flights between IAH_EAST and its modification.

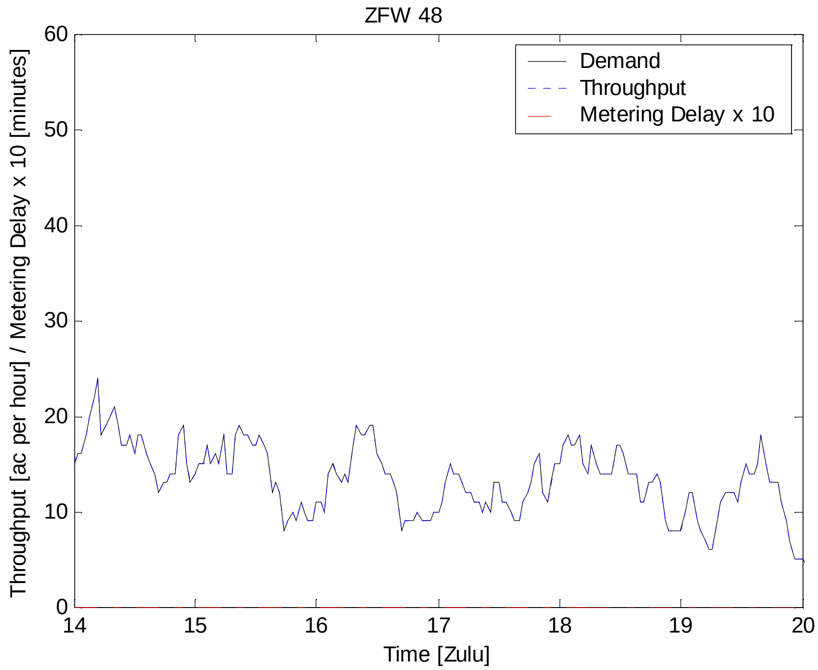


Figure 28. Throughput and Delay results for ZFW48 on the IAH_EAST modification, August 16, 2002 after allocation of flights between IAH_EAST and its modification.

Figure 27 can be compared to Figure 18 to see the effect of allocating some flights to the alternative playbook reroute. It is clear that delay has been reduced considerably, especially between 15:00 and 16:00.

Figure 28 shows that no metering is required on the alternative reroute, which has been allocated 16 flights. The congestion on the original playbook, shown in Figure 27 is not enough to cause more flights to be allocated to the longer alternative. In this way, the delay is spread over two reroutes, resulting in a delay saving of 718 minutes.

c) Allocate Between Playbook Reroute and Airline Alternative

This case introduces an element of airline collaboration into the decision of how to reroute flights around an FCA. A customized alternative reroute is identified to represent the airlines' choice to reduce flight distance. The FAA then allocates flights between this airline alternative and the original playbook reroute. This is a simplified scenario to model the effect of airline collaboration[14]. For the cases of the CAN_1_EAST reroute on June 11, 2003, the VUZ reroute on September 15, 2002 and the IAH_EAST reroute on August 16, 2002, airline alternative reroutes were generated according to the method described in Section 5.2. In the case of the VUZ alternative this was done by fabricating an alternative from a number of playbook reroutes. The airline alternative

[14] This airline collaboration is simplified by assuming the all airlines suggest a single airline alternative reroute. This may be improved by considering a different airline alternative reroute for each airline. Other factors that come into the airline's decision might also be introduced, such as missed connections.

reroute to CAN_1_EAST is represented by the most congested sector ZOB36, while the airline alternative reroute to VUZ is represented by most congested sector ZKC31. The airline alternative reroute to IAH_EAST is represented by the most congested sector ZFW48.

For the other two reroute examples – BUM and DFW_EAST – it was not possible to identify an alternative route that appeared to be better than the playbook alternative chosen. Rather than force an airline alternative that the airlines would probably not have chosen, it was decided in these cases that the airline would suggest the same alternative playbook reroute identified in Section 6.1.2.1 above, in each case. Thus, for these examples, the allocation between the original playbook reroute and an airline alternative becomes identical to the allocation between two playbook reroute alternatives presented in Table 3. Figure 29, Figure 30 and Figure 31 show the airline alternative reroutes alongside the original playbook and alternative playbook reroutes for the CAN_1_EAST reroute on June 11, 2003, the VUZ playbook reroute on September 15, 2002 and the IAH_EAST reroute on August 16, 2002 respectively.

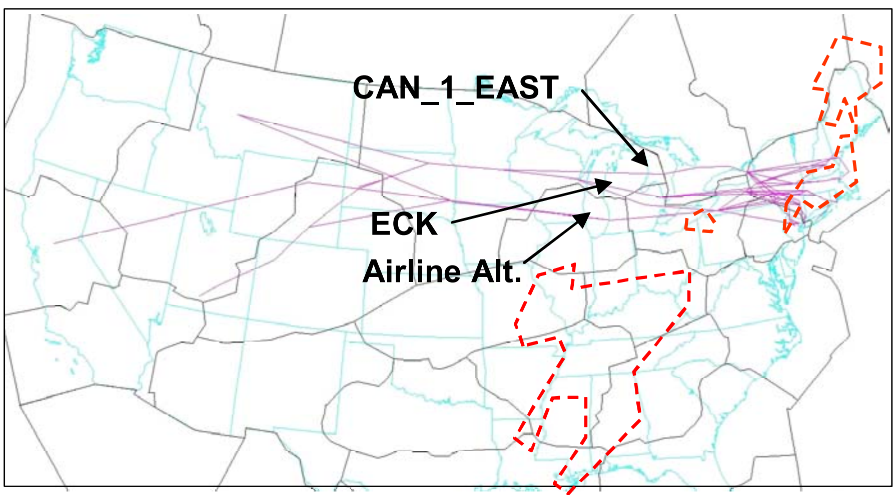


Figure 29. Map showing playbook reroute CAN_1_EAST, alternative playbook reroute ECK and the airline alternative reroute.

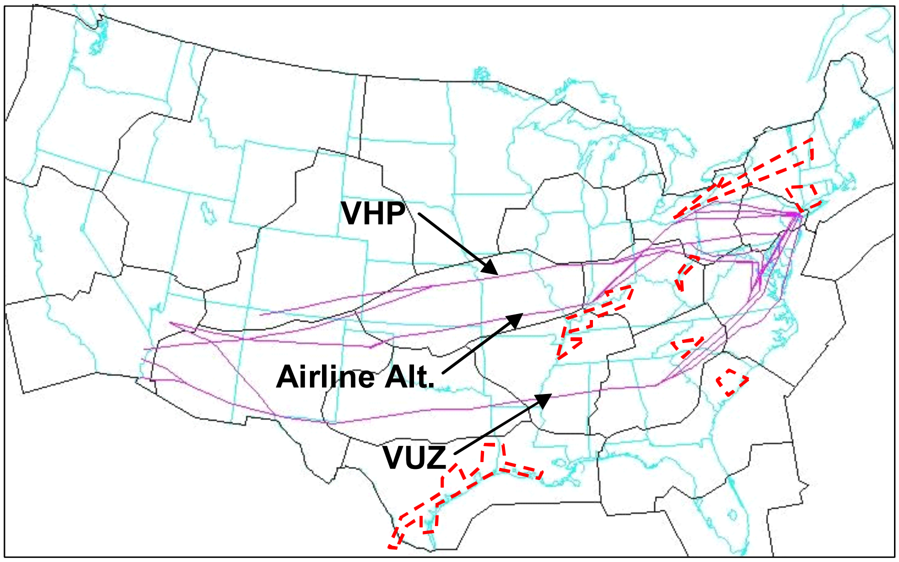


Figure 30. Map showing playbook reroute VUZ, alterative playbook reroute VHP and the airline alternative reroute.

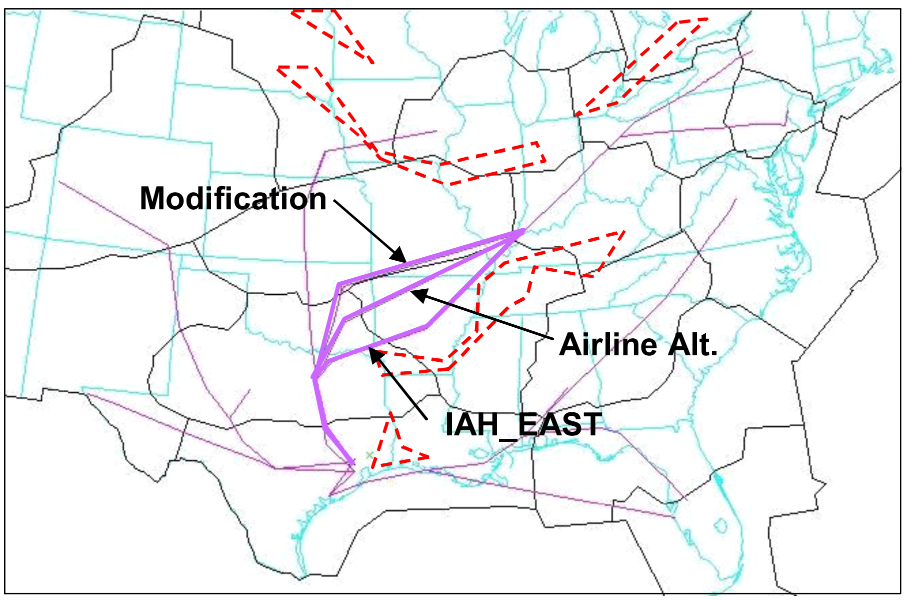


Figure 31. Map showing playbook reroute IAH_EAST, alternative playbook reroute identified by the word "Modification" and the airline alternative reroute.

Table 4 shows the results of the analysis for all examples. For FAM and DFW_EAST, these are the same results as presented in Table 3.

Table 4. Delay Statistics for allocation between the original playbook reroute and an airline customized alternative reroute.

Scenario	Alt. Reroute	# of Flts Rerouted	# of Flts on Original	# of Flts on Alt.	# of Flts Metered	Total Delay [min]	Reroute Delay [min]	Metering Delay [min]	Delay Saving [min]
CAN_1_EAST Reroute on June 11, 2003									
Baseline	-	103	103	-	240	1269	669	600	**-**
Allocation	AIRLINE	103	29	74	517	224	214	10	**1047**
VUZ Reroute on September 15, 2002									
Baseline	-	57	57	-	193	2039	1825	214	**-**
Allocation	AIRLINE	57	0	57	368	10	2	8	**2012**
FAM Reroute on August 16, 2002									
Baseline	-	46	46	-	291	573	469	104	**-**
Allocation	BUM	46	21	25	435	377	337	40	**196**
IAH_EAST Reroute on August 16, 2002									
Baseline	-	83	83	-	295	2355	2144	211	**-**
Allocation	AIRLINE	83	29	54	486	1069	1024	425	**1286**
DFW_EAST Reroute on September 19, 2002									
Baseline	-	369	369	-	632	7405	7375	30	**-**
Allocation	Mod	369	235	134	978	5816	5785	31	**1589**

In comparing these results to the allocation between two playbook reroutes, a comparison can only be made with the VUZ playbook reroute on September 15, 2003 and the IAH_EAST playbook reroute on August 16, 2003. When compared to the benefit of 1937 minutes shown in Table 3 for allocation between two playbook reroutes, it is apparent that the customized selection of an alternative reroute gives benefits of 2012minutes, i.e. an improvement of 75minutes. The criteria used for customization of an airline preferred reroute can however be vastly improved over that used in this example – i.e. to reduce flight distance.

Figure 32 shows demand, throughput and delay on August 16, 2002 for ZFW42 on IAH_EAST after the flights have been allocated according to Table 4. Figure 33 shows demand, throughput and delay for ZFW48, which is the most congested sector identified on the airline alternative reroute.

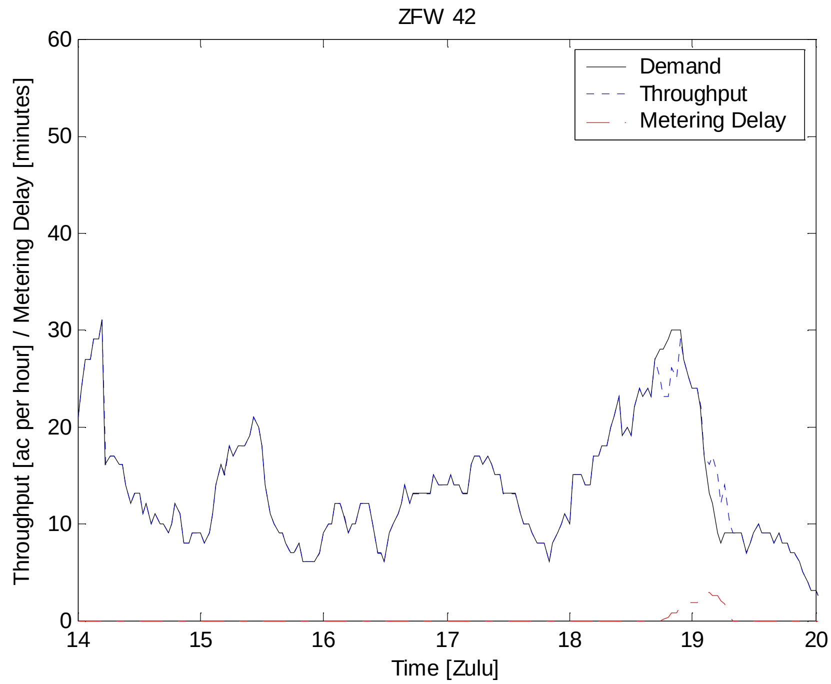


Figure 32. Throughput and Delay results for ZFW42 on the IAH_EAST reroute, August 16, 2002 after allocation of flights between IAH_EAST and the airline alternative.

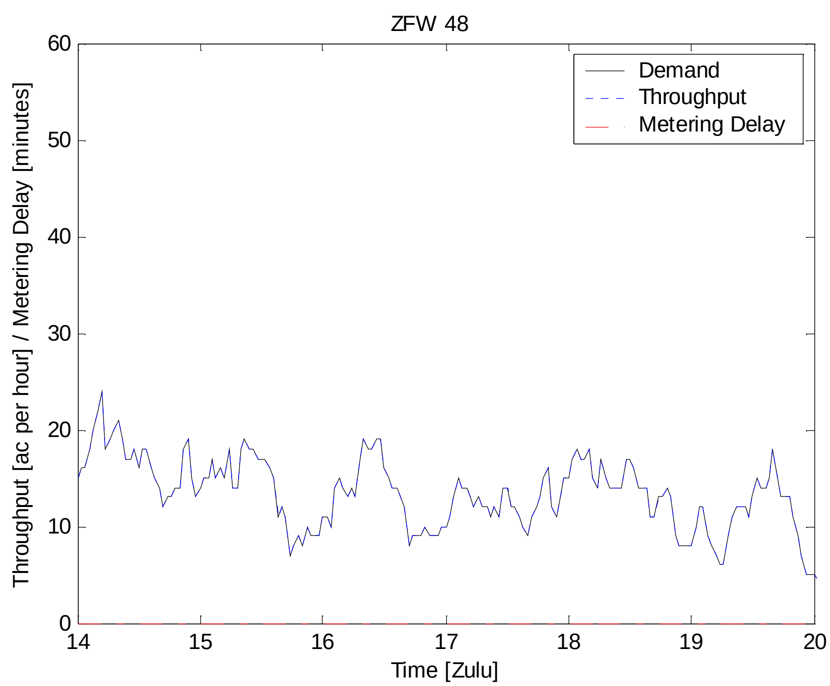


Figure 33. Throughput and Delay results for ZFW48 on the airline alternative reroute, August 16, 2002 after allocation of flights between IAH_EAST and the airline alternative.

Figure 32 shows that, as in the case of the allocation between playbook reroutes, the need for metering for ZFW42 has been reduced. In this case, it has been reduced to a far greater degree however than is seen in Figure 27. Far fewer flights are left on the original playbook reroute – 29 versus 67 in the case of the allocation between playbook reroute. ZFW48 is also not congested, despite having 54 flights allocated to it. This indicates the suitability of this airline alternative, both in terms of reroute distance and congestion.

6.2. Airspace Redesign: Airspace Dynamic Resectorization

The results following have been calculated applying an airspace resectorization to the three transcontinental playbook reroutes simulated to model rerouting around an FCA. These were CAN_1_EAST on June 11 2003, VUZ on September 15 2002, and FAM on August 16 2002. The performance benefits of using SWEPT for airspace resectorization are presented for each case. The delay benefits presented are total delay savings over the duration of the reroute, including metering delay savings of rerouted flights and other flights in the critical overloaded sector requiring metering. The benefit in delay over the case without airspace resectorization comes only from reduced metering delay, as the flights are assumed to fly the same flight paths as before the airspace resectorization. The amount of metering required is affected by the airspace resectorization, as the resectorization affects the sector loadings.

6.2.1. Baseline

The baseline in the airspace resectorization problem is identical to that in rerouting around an FCA, comprising a simulation of a playbook reroute applied in response to weather. The resources identified for resectorization are the same as those identified to be the primary flow constraints in the FCA problem, as follows:

CAN_1_EAST on June 11, 2003:	ZMP12
VUZ on September 15, 2002:	ZFW82
FAM on August 16, 2002:	ZID91

The total delays under this baseline, relative to no reroute, are presented in Section 6.1.1, Table 1.

6.2.2. Improved Metering through Airspace Resectorization

Instead of choosing metering or rerouting around an overloaded sector, the overloaded constraining sector can be resectorized to distribute the workload across other controllers working adjacent, uncongested sectors, as described in Section 5.3. This was simulated for the most congested sectors on the baseline reroutes on June 11 2003, September 15 2002, and August 16 2002.

For the CAN_1_EAST playbook reroute on June 11 2003, ZMP12 was resectorized by moving the boundary between ZMP12 and ZMP13 to decrease the size of ZMP12, while increasing the size of ZMP13. Figure 34 below shows the details of the resectorization. The sector boundary is moved so that aircraft on the playbook reroute still all pass through the sector, but spend less time in the sector. The sector capacities were initially maintained constant. This assumes that sector capacity is constrained by controller workload and not airspace, and that controller workload is not increased significantly as sector size is decreased. Because it is not clear that controller workload does not in fact increase, sector capacity was also reduced as part of a sensitivity analysis, and the results recalculated. Sector capacity was reduced by 10% for this analysis as this results in a sector capacity that compares more closely to that of other sectors of similar size. For ZMP12 this reduces the sector capacity from 20 aircraft to 18 aircraft.

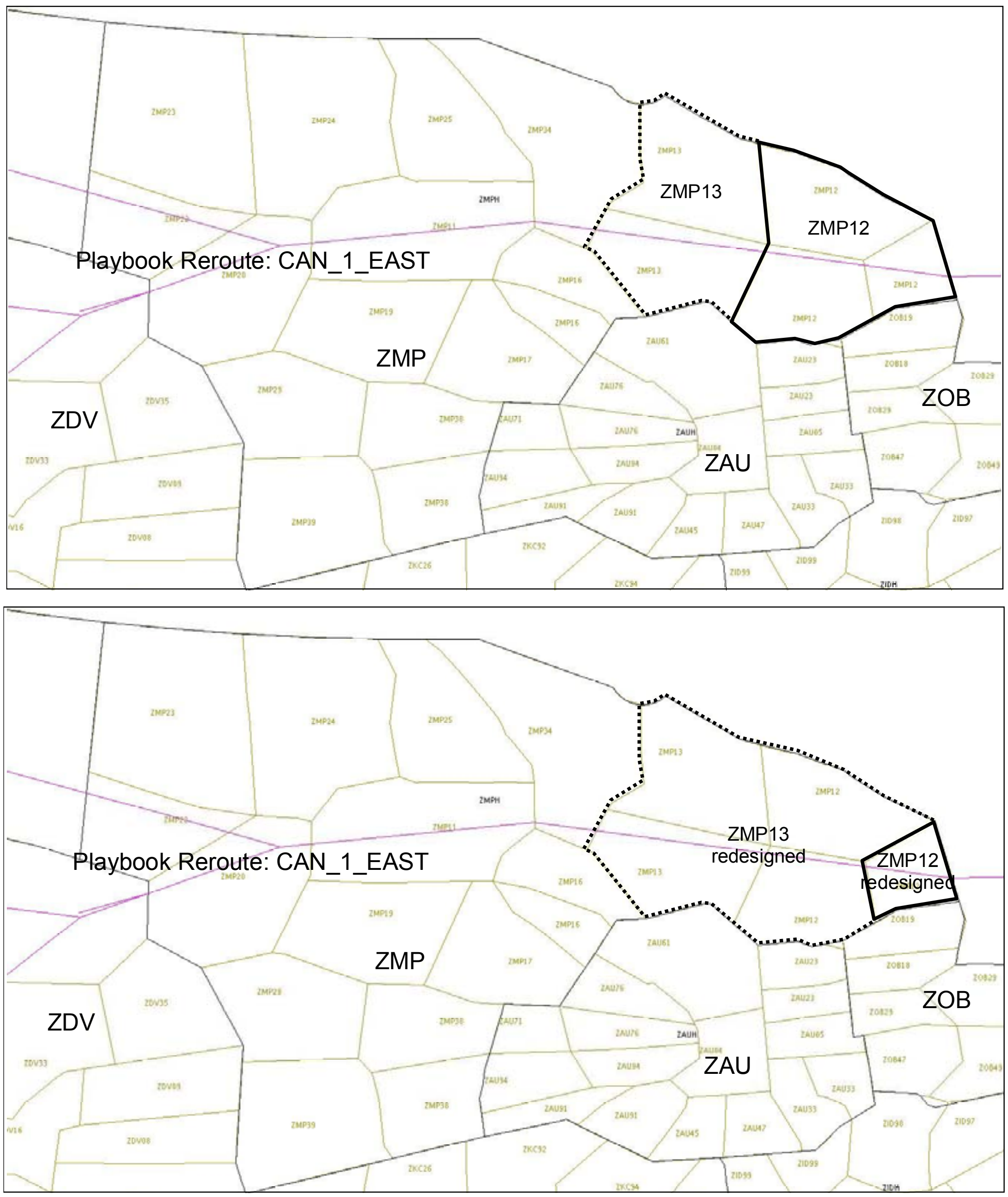


Figure 34. ZMP12 (solid line) and ZMP13 (dotted line) before and after airspace resectorization.

For the VUZ playbook reroute on September 15, 2002, ZFW82 was resectorized by moving the boundary between ZFW82 and ZFW65 to decrease the size of ZFW82, while increasing the size of ZFW65. As in the CAN_1_EAST case, the sector boundary is moved so that aircraft on the playbook reroute still all pass through the sector, but spend less time in the sector. The results were again calculated assuming sector capacities remain constant, and assuming a 10% decrease in sector capacity. This reduces the sector capacity of ZFW82 from 18 aircraft to 16 aircraft. Figure 35 below shows the details of the resectorization.

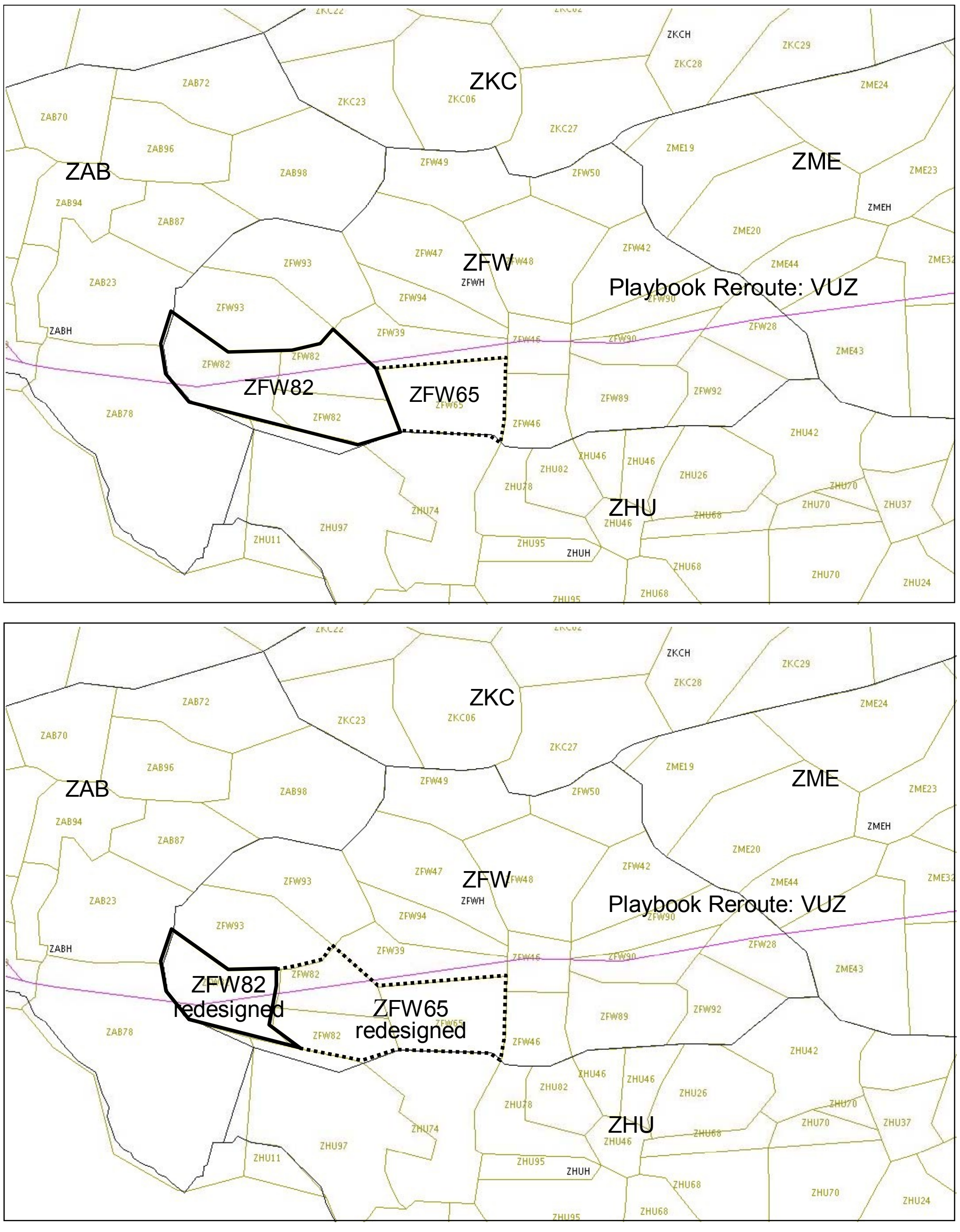


Figure 35. ZFW82 (solid line) and ZFW65 (dotted line) before and after airspace resectorization.

For the FAM playbook reroute on August 16, 2002, ZID91 was resectorized by moving the boundary between ZID91 and ZID99 to decrease the size of ZID91, while increasing the size of ZID99. The sector boundary is moved so that aircraft are split between the two sectors, so that less aircraft enter the constrained sector. The boundary is moved, however, in such a way as to avoid an increase in hand offs between controllers. This is done by moving the boundary in such a way as to avoid any portion of the specified playbook reroute (FAM) entering ZID99, the adjacent uncongested sector. The results were again calculated assuming sector capacities remain constant, and assuming a 10% decrease in sector capacity. This reduces the sector capacity of ZID91 from 17 aircraft to 15 aircraft. Figure 36 below shows the details of the resectorization.

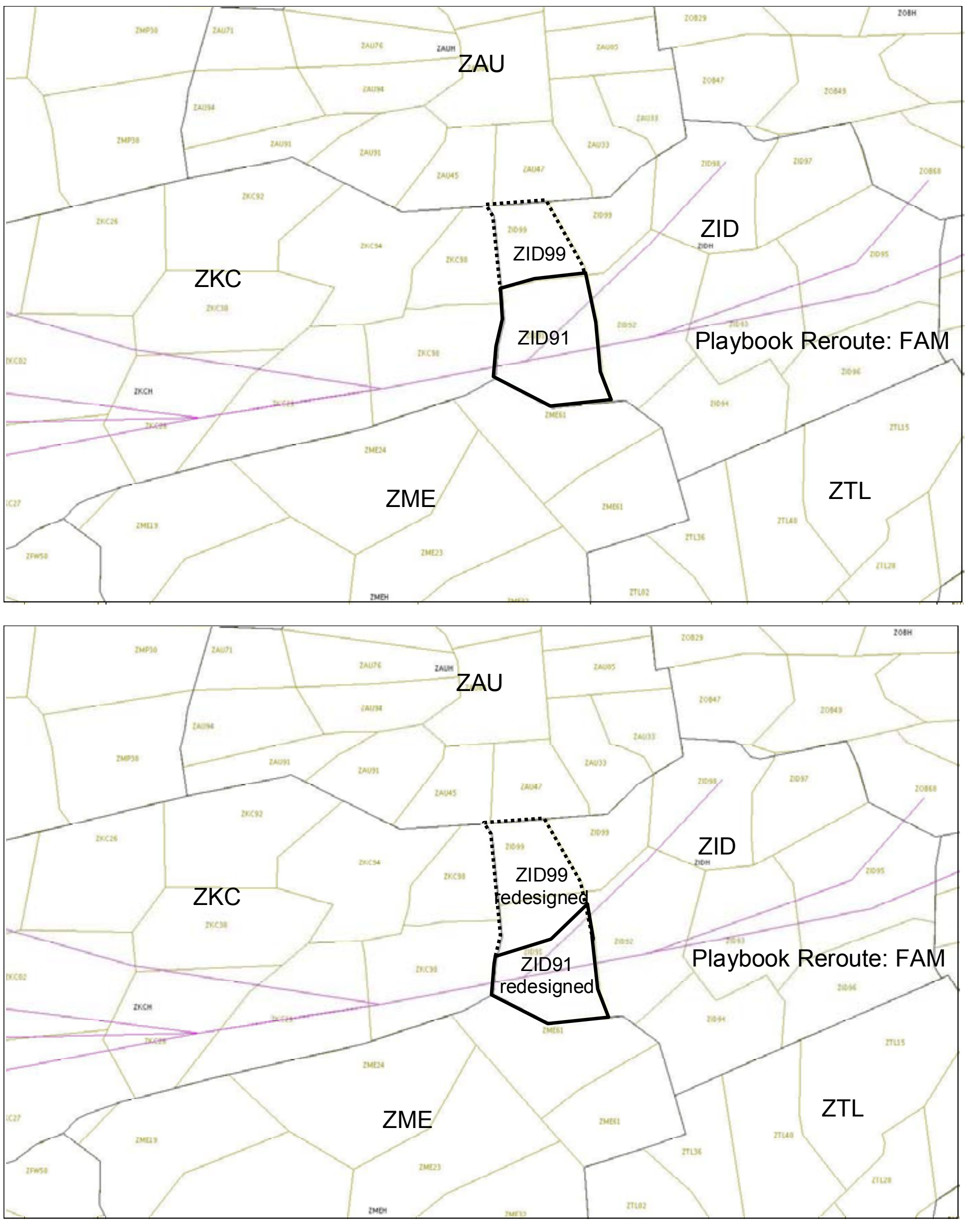


Figure 36. ZID91 (solid line) and ZID 99 (dotted line) before and after airspace resectorization.

The resulting delay savings, after application of metering to reduce sector loading below capacity, are presented in the tables below for each playbook reroute. These savings are relative to the delays incurred under the baseline operations, with no sector resectorization, as presented above in Table 1. Table 5 shows the results with no decrease in the resectorized sector capacity, while Table 6 shows the results with a 10% decrease in the resectorized sector capacity.

No Decrease in Resectorized Sector Capacity

Table 5. Delay statistics for airspace resectorization with no decrease in resectorized sector capacity.

Scenario	# of Flts Rerouted	# of Flts Metered	Total Delay [min]	Delay Saving [min]
CAN_1_EAST Reroute on June 11, 2003				
Baseline	103	240	1267	**-**
Resectorization	103	242	898	**369**
VUZ Reroute on September 15 2002				
Baseline	57	193	2022	**-**
Resectorization	57	159	1825	**197**
FAM Reroute on August 16, 2002				
Baseline	46	291	562	**-**
Resectorization	46	275	473	**89**

The delay savings over the baseline are higher for CAN_1_EAST on June 11, 2003 than for VUZ on September 15, 2002, which are in turn higher than for FAM on August 16, 2002. This is primarily because of the number of flights affected by the respective reroutes, as discussed in Section 6.2. As an example, Figure 37 below shows the demand, throughput and metering delay on September 15, 2002 in ZFW82, before and after the airspace resectorization. Similar plots for the other two cases show the same effects.

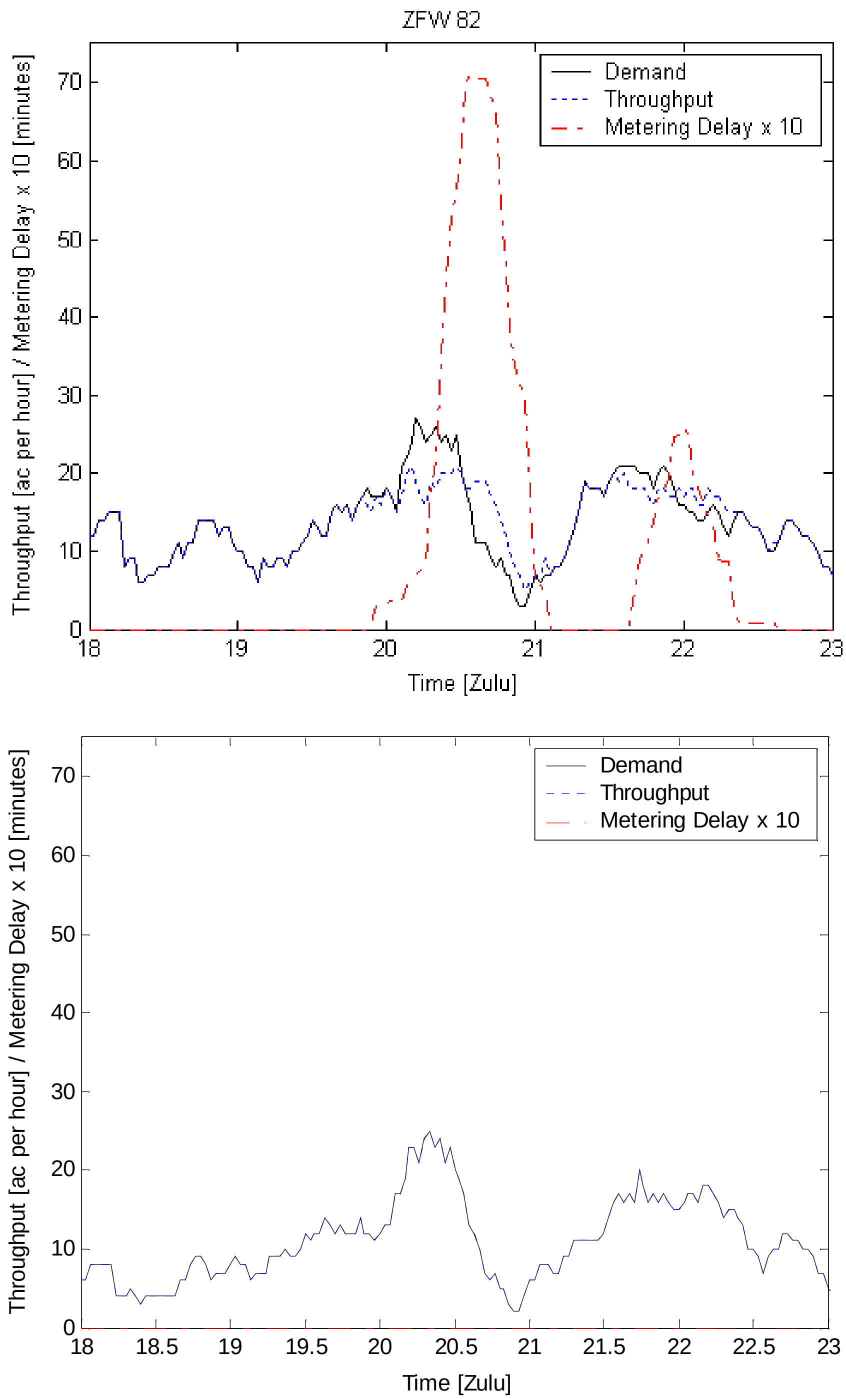
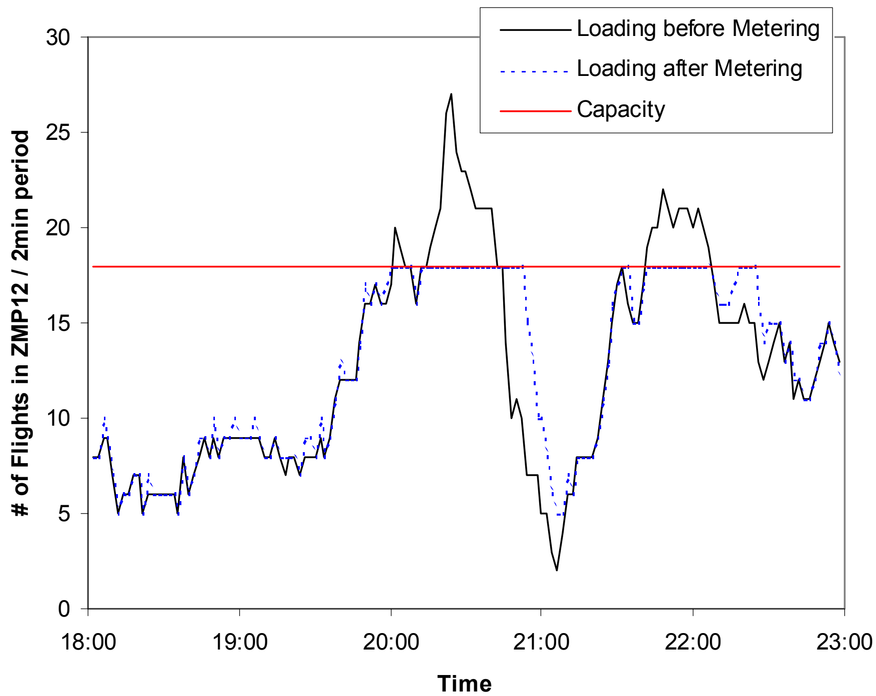


Figure 37. Throughput and metering delay results for sector ZFW82 on the VUZ reroute, September 15, 2002, before (baseline) and after airspace resectorization.

It is clear from the figures that metering delay is reduced completely, while demand remains approximately the same. Demand remains approximately the same because the same aircraft still fly through the sector. The aircraft spend less time in the sector, so the sector loading is reduced. This allows for increased throughput after metering, which is able to match demand more closely after the resectorization. Figure 38 below shows the sector loading verses capacity for ZFW82 on September 15, 2002, before and after metering for the baseline ZFW82, and the resectorized ZFW82.



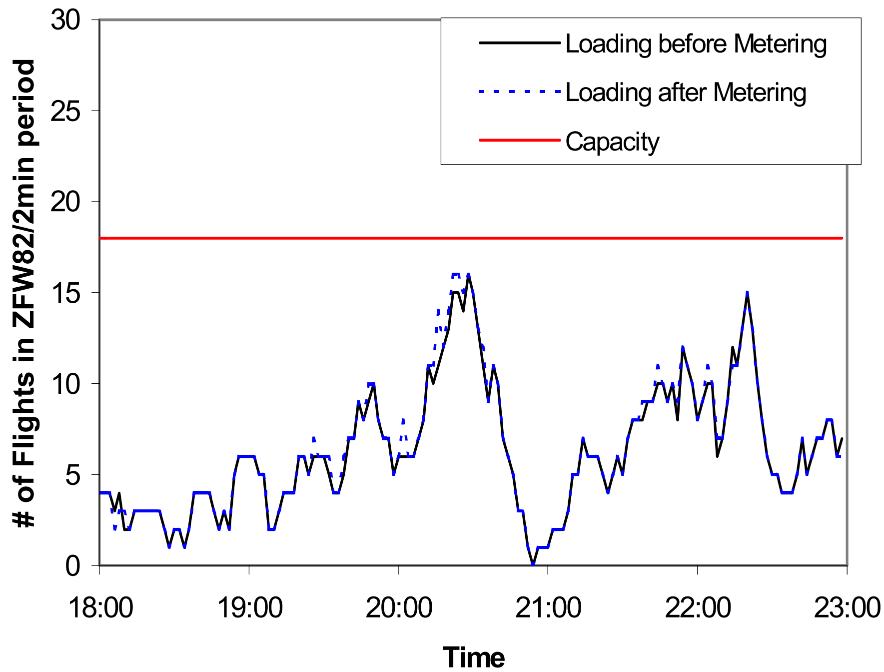


Figure 38. Sector loading versus time of ZFW82 as simulated by FACET on September 15, 2002 with the VUZ playbook reroute in place, before (baseline) and after airspace resectorization.

It is clear from the plots of sector loading in Figure 38 that sector loading is reduced after the airspace resectorization. Sector loading is reduced to such an extent in fact that metering is no longer required. The approach does thus show delay savings, as presented in Table 3.

10% Decrease in Resectorized Sector Capacity

Table 6. Delay statistics for airspace resectorization with 10% decrease in resectorized sector capacity.

Scenario	# of Flts Rerouted	# of Flts Metered	Total Delay [min]	Delay Saving [min]
CAN_1_EAST Reroute on June 11, 2003				
Baseline	103	240	1267	**-**
Resectorization	103	242	1498	**-231**
VUZ Reroute on September 15 2002				
Baseline	57	193	2022	**-**
Resectorization	57	159	1825	**197**
FAM Reroute on August 16, 2002				
Baseline	46	291	562	**-**
Resectorization	46	275	549	**13**

In the CAN_1_EAST case the benefits are clearly negative when the sector capacity is reduced by 10%. This is because the sector loading after the resectorization is high, and a reduction of the sector capacity causes the sector to be overloaded in a number of time slots. The resulting metering required is greater than was initially required with no resectorization. It is important to note that it is not clear how much sector capacity should actually be reduced given the resectorization implemented. More analysis of the sector traffic flows would be required to select the most appropriate reduction. The 10% decrease in sector capacity instead represents an indication of the sensitivity of the benefits to sector capacity. If this reduction in sector capacity were to be applied operationally, the resectorization would not be implemented as the benefits are negative. The benefits if TFM R&D to this case would thus be zero.

In the VUZ case the benefits do not change from those with no decrease in sector capacity, presented in Table 5. This is because the sector loading after resectorization was sufficiently low that a 10% decrease in sector capacity did not cause the sector to be overloaded during any time slots. This is clearly a very different case to the CAN_1_EAST case discussed above.

In the FAM case the benefits are reduced, but not below zero. This means that the decrease in sector capacity had caused the sector to be overloaded in some time slots, but not so many as to make the original sectorization better than that after resectorization.

6.3. Pre-emptive Airline Collaboration

Each of the example reroutes analyzed in Section 6.1 was used to investigate how pre-emptive action by the airlines increases savings, as described in Section 5.4. With each example, two cases were considered. In the first case, one airline is assumed to use FACET-AOC. This airline anticipates the playbook reroute and allocates its flights between this playbook reroute and another alternative customized by the airline. All other flights are assumed to be on the original playbook reroute. The airline then re-files the flight plans of those allocated to the airline alternative reroute. The FAA then implements the original playbook reroute and any metering required. The second case is identical to the first except that all airlines are assumed to have FACET-AOC, and therefore be able to allocate and re-file some of their flights to an airline alternative. The FAA responds by implementing the playbook reroute on flights that have not been re-filed by the airlines and by implementing any metering required.

To simplify the analysis, the airline alternative reroutes suggested by the airlines were assumed identical to the airline alternatives introduced collaboratively in Sections 0.

6.3.1. Preemptive Action by One Airline

For the purposes of this simulation, the airline that had the most flights rerouted by the particular playbook reroute in question was chosen. The scenario assumes that the airline correctly anticipates the playbook reroute and which flights it will affect. For the CAN_1_EAST playbook reroute on June 11, 2003, on which 103 flights were rerouted, Continental Airlines (COA) was found to have the most rerouted flights at 20 flights. COA was therefore chosen to carry out preemptive action on June 11, 2003. The examples are summarized as follows:

- CAN_1_EAST on June 11, 2003: of the 103 flights, COA was chosen with 20 flights
- VUZ on September 15, 2002: of the 57 flights, AWE was chosen with 12 flights
- FAM on August 16, 2002: of the 46 flights, UAL was chosen with 9 flights
- IAH_EAST on August 16, 2003: of the 83 flights, COA was chosen with 39 flights
- DFW_EAST on September 19, 2003: of the 369 flights, AAL was chosen with 169 flights

The analysis results are shown in Table 7.

Table 7. Delay Statistics for Preemptive action by a single airline.

Scenario	Reroute	# of Flts Rerouted	# of Flts on Reroute	# of Flts Metered	Total Delay [min]	Delay Saving to One Airline [min]	Delay Saving to Rest of Airlines [min]	Total Delay Saving [min]
CAN_1_EAST Reroute on June 11, 2003								
Baseline	CAN_1_EAST	103	103	240	1269	-	-	**-**
Pre-emptive Collaboration	CAN_1_EAST	103	88	517	666	478	120	**498**
	Airline Alt.		15					
VUZ Reroute on September 15, 2002								
Baseline	VUZ	57	57	193	2039	-	-	**-**
Pre-emptive Collaboration	VUZ	57	45	368	1224	332	92	**424**
	Airline Alt.		12					
FAM Reroute on August 16, 2002								
Baseline	FAM	46	46	291	573	-	-	**-**
Pre-emptive Collaboration	FAM	46	39	435	405	45	19	**64**
	BUM		7					
IAH_EAST Reroute on August 16, 2002								
Baseline	IAH_EAST	83	83	295	2355	-	-	**-**
Pre-emptive Collaboration	IAH_EAST	83	63	486	1333	432	149	**581**
	Airline Alt.		20					
DFW_EAST Reroute on September 19, 2002								
Baseline	DFW_EAST	369	369	632	7405	-	-	**-**
Pre-emptive Collaboration	DFW_EAST	369	291	978	4016	859	71	**930**
	Modification		78					

Of the 20 COA flights anticipated to be affected by the CAN_1_EAST playbook reroute on June 11, 2003, 15 are allocated preemptively to the airline alternative reroute. The remaining 5 COA flights and all other airline flights (i.e. a total of 88 flights) are then rerouted by the FAA on CAN_1_EAST. The total number of flights – including rerouted flights and other flights passing through the most congested sectors identified –

metered following the rerouting is 517. Of the total delay saving of 498 minutes, 478 belong to COA. This is distributed over the 20 COA flights rerouted as will as 16 other COA that passed through the most congested sectors ZMP12 and ZOB36. Clearly, preemptive action by COA has given them a significant benefit, and has even given their competitors some delay saving.

The results for the other reroutes show similar trends to that of CAN_1_EAST. Of particular interest are the two airport closures, as they apply to hub airports for COA in the case of IAH and AAL in the case of DFW. These were the airlines chosen to have FACET-AOC and hence carry out preemptive action in these examples. The results show the significant benefit, particularly in the case of DFW_EAST of the airline (in this case AAL) using FACET-AOC. The reason for the large delay savings by the airline is the large number of flights belonging to that airline – and in particular AAL flights (169) – that are affected by the reroute.

6.3.2. Preemptive Action by All Airlines

In this scenario, all airlines allocate their flights between the anticipated playbook reroute, and the airline alternative. Flights allocated to the airline alternative reroute have their flight plans re-filed. The FAA then implements the playbook reroute on all flights that have not had the flight plans re-filed. This scenario, although slightly different in practice, is identical in numbers to the scenario discussed in Section 0 where the FAA allocates flights between the original playbook reroute and an airline customized alternative. This is because the algorithm used does not explicitly distinguish the timing of the action – i.e. the results are the same whether the airlines allocate over the two reroute alternatives first, followed by the FAA implementing the original playbook reroute on those aircraft allocated to it; or the FAA allocating over the same reroutes and then implementing them. The results for this analysis are shown in Table 4 and are repeated below in reduced form in Table 8, so that comparison can be made to Table 7.

The relative benefits of each example shall not be discussed again here, as the trends have already been discussed in Section 6.1.2.2. What is interesting is to compare the results relative to those for one airline preempting the FAA (see Table 7). In all cases except CAN_1_EAST, the individual airlines using FACET-AOC see similar delay savings in both scenarios. The other airlines however see a far greater delay saving when they too use FACET-AOC for pre-emptive action. The total delay savings are accordingly higher as well. This is because all flights now have the opportunity of choosing the airline alternative reroute, and that now all flights are distributed over the two reroutes, rather than just the individual airline, as was the case in Table 7.

In the case of the CAN_1_EAST reroute, the individual airline (COA in this case) sees a decrease in its savings when all airlines use FACET-AOC. This is because the reroute alternative is close to capacity before any aircraft are rerouted on it. When all airlines have the option of rerouting on this alternative, delays are incurred. COA did not have enough flights to incur these delays on their own.

Table 8. Delay Statistics for preemptive action by all airlines.

Scenario	Reroute	# of Flts Rerouted	# of Flts on Reroute	# of Flts Metered	Total Delay [min]	Delay Saving to One Airline [min][15]	Delay Saving to Rest of Airlines [min]	Total Delay Saving [min]
CAN_1_EAST Reroute on June 11, 2003								
Pre-emptive Collaboration	CAN_1_EAST	103	29	517	224	112	935	**1047**
	AIRLINE		74					
VUZ Reroute on September 15, 2002								
Pre-emptive Collaboration	VUZ	57	0	368	10	336	2012	**2012**
	AIRLINE		57					
FAM Reroute on August 16, 2002								
Pre-emptive Collaboration	FAM	46	21	435	377	51	145	**196**
	BUM		25					
IAH_EAST Reroute on August 16, 2002								
Pre-emptive Collaboration	IAH_EAST	83	29	486	1069	432	854	**1286**
	Modification		54					
DFW_EAST Reroute on September 19, 2002								
Pre-emptive Collaboration	DFW_EAST	369	235	978	5816	847	742	**1589**
	Modification		134					

[15] The One Airline referred to is the airline which used FACET-AOC on its own in Table 7, i.e. COA in the case of CAN_1_EAST, AWE in the case of VUZ, UAL in the case of FAM, COA in the case of IAH_EAST, and AAL in the case of DFW_EAST.

7. TFM R&D Economic Benefits

The ultimate benefits of TFM R&D identified from the analysis of the benefit mechanisms in Section 5 are fuel savings, reduced en-route delay, reduced arrival delay, increased throughput, and reduced arrival delay of high priority flights. These benefits are related to each other, and result in direct economic benefits according to the chart in Figure 39 below.

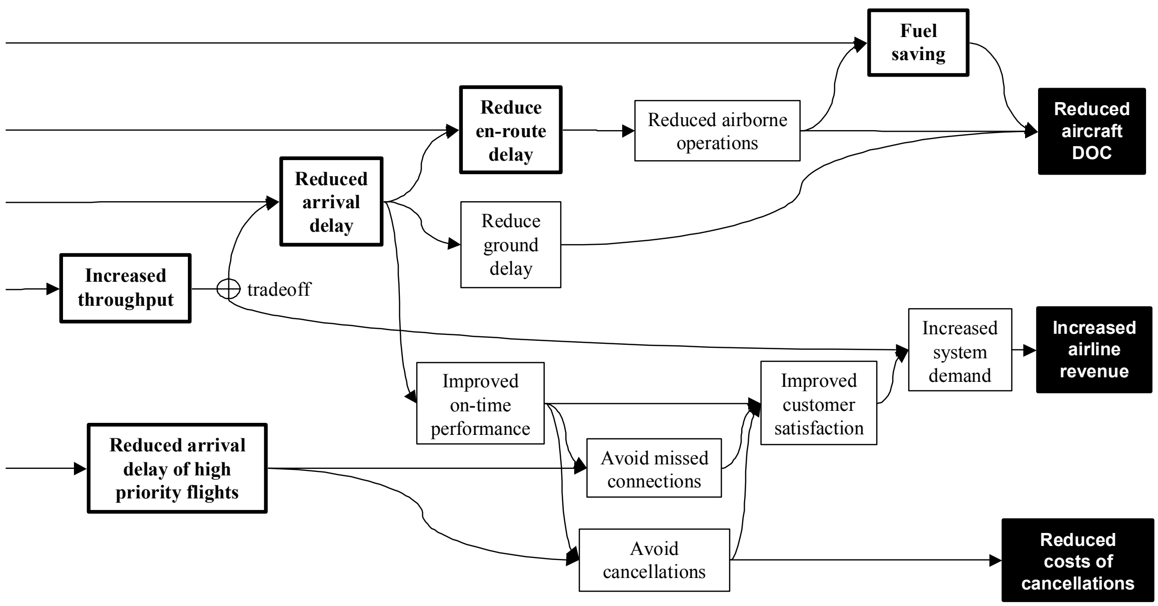


Figure 39. Direct economic benefits.

Savings in fuel burn result directly in a reduction in aircraft direct operating costs (DOC), as fuel is an aircraft direct operating cost.

Reduced en-route delay results directly in reduced airborne operations. Because fuel burn is related directly to airborne operations, a reduction in airborne operations also results in a reduction in fuel burn. Direct operating costs are reduced by this reduction in fuel burn, and in the reduction in other direct operating costs related to airborne operations, such as crew costs. The dollar benefits of reduced aircraft direct operating costs are calculated for the three cases studied. The results are presented in Section 7.1.1 below.

If aircraft arrival delay is reduced it can manifest as a reduction in ground delay or a reduction in en-route delay. A reduction in en-route delay results in a reduction in airborne operations and thus aircraft direct operating cost. A reduction in ground delay results directly in a reduction in direct operating cost. A reduction in arrival delay also results directly in an improvement in on-time performance, as recorded and published by the FAA. This means that some missed connections and cancellations are avoided, and that customer satisfaction with the airline is improved. Avoiding cancellations also reduces the costs associated with such cancellations. Improved customer satisfaction increases demand, and correspondingly increases airline revenue as more people fly with the airline. As described above, the dollar benefits of reduced aircraft direct operating costs are calculated for the three cases studied, as presented in Section 7.1.1 below. Dollar benefits are not however calculated for increased airline revenue or the reduced costs of cancellations.

An increase in system throughput can allow for either a reduction in arrival delay or an increase in demand. As throughput increases, if demand is not increased, arrival delay will decrease. However, if demand is increased when throughput increases, arrival delay may not decrease at all. This is because arrival delay increases if demand increases, when throughput remains constant. There are however benefits to both responses. A decrease in arrival delay would reduce aircraft direct operating costs. An increase in demand, however, would increase revenue. There is thus a tradeoff between delay and demand. The level of demand and delay at which the airlines will operate is likely to be near the point of maximum profit, or at some acceptable level of system utilization. The point of maximum profit is illustrated in Figure 40 below, relative to demand.

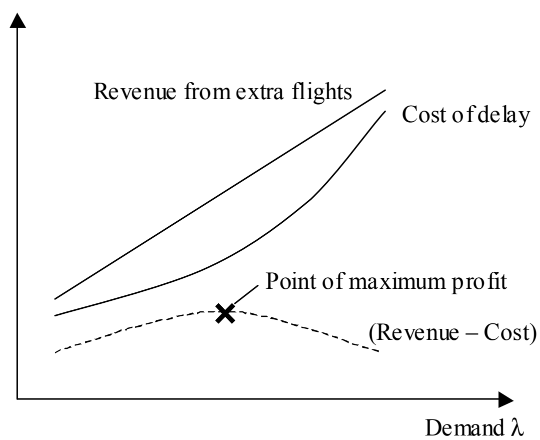


Figure 40. Costs and revenues associated with increasing demand

With an increase in throughput, demand will thus be increased until the point of maximum profit is reached, or to the point where the system utilization (demand over capacity) matches current levels of system utilization. The airlines are unlikely to increase demand above this level of utilization because it represents a level of delay acceptable to the flying public. Any higher utilization would result in unacceptable delays and would drive away customers.

A reduction in the arrival delay of high priority flights is dependent on the priorities of the airline. However, in general, high priority flights are those that result in fewer missed connections and cancellations. Consequently a reduction in the arrival delay of high priority flights would result in fewer missed connections and cancellations. As described above, fewer missed connections and cancellations are likely to improve customer satisfaction, which results in increased demand. Reduced cancellations reduces the costs associated with canceling a flight, such as the costs associated with accommodating passengers on the cancelled flights by paying for a hotel, or paying for a flight on another aircraft.

7.1. *Overview of Modeling Methodology*

According to Figure 39 the direct economic benefits include reduced aircraft direct operating costs, increased airline revenue, and reduced costs of cancellations. Only reduced aircraft direct operating cost is calculated in this study, as presented below.

7.1.1. Direct Operating Cost Savings

Delay that must be absorbed by metering can be absorbed either en-route, or on the ground. The direct operating cost of delay is higher if it is absorbed en-route, because of the added costs of fuel burn. Fuel is not burned if delay is absorbed on the ground. The amount of delay to be absorbed en-route and on the ground was identified for each modeled flight individually, by comparing the total amount of delay to be absorbed by metering, for each flight, to an average historical breakdown of delay absorption for that level of total delay. The average historical amount of delay absorbed en-route and on the ground was calculated from historical data, as a function of total delay. This breakdown of en-route and ground delay was then applied to each flight dividing the total delay incurred by each flight into en-route and ground components. The historical data analysis was completed from the FAA Aviation System Performance Metrics (ASPM) database for September, October and November 2002, for all arrivals into Newark International Airport (EWR), LaGuardia Airport (LGA), John F Kennedy International Airport (JFK), Teterboro Airport (TEB), and Philadelphia International Airport (PHL). These airports were analyzed because the data was available from the NASA RTO 77 [2] research. A plot of delay absorbed en-route versus total delay absorbed is presented in Figure 41. For each level of total delay, an average en-route delay can be identified. Average ground delay can be calculated accordingly by subtracting en-route delay from total delay.

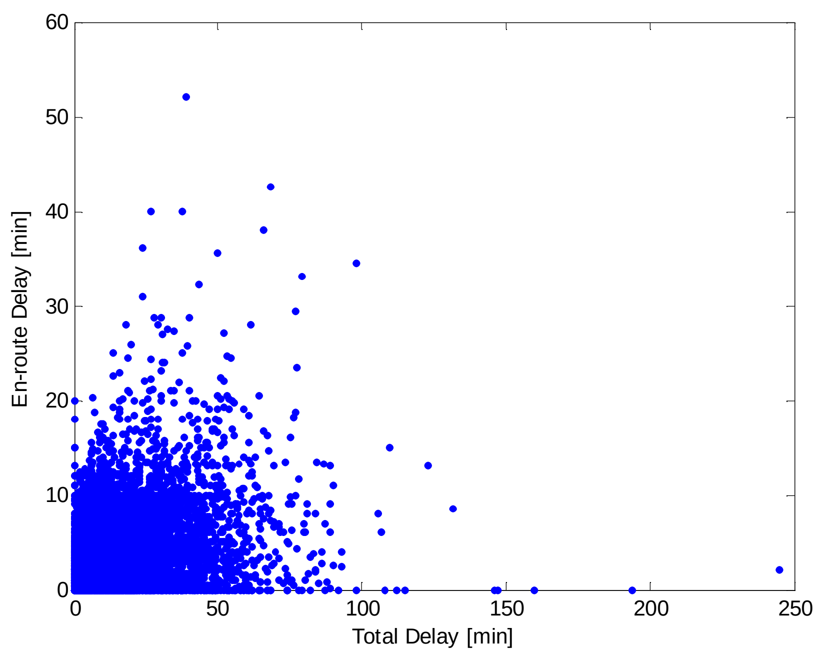


Figure 41. Historical breakdown of delay absorption (ASPM - Sept., Oct., Nov. 2002, for EWR, LGA, JFK, TEB, and PHL).

Average aircraft operating costs per hour were estimated according to the FAA's 2002 update [8] to the Executive Summary tables in FAA-APO-98 [9]. Average total aircraft operating cost per hour, for scheduled commercial service, was identified as US$ 3,285. This applies to in air operations, as fuel and oil costs are included. Fuel and oil costs are only incurred in the air, while all other costs are incurred both on the ground and in the air. Excluding the costs of fuel and oil, average aircraft operating cost per hour on the ground was identified as US$ 2,412. The cost of the en-route delay of each flight was then calculated by multiplying the delay absorbed en-route by the average aircraft operating cost per hour en-route. Delay absorbed en-route includes the metering delay absorbed en-route, and the reroute delay resulting from the longer flight path of the reroute. The cost of the ground delay of each flight was then calculated by multiplying the delay absorbed on the ground by the average aircraft operating cost per hour on the ground. The delay absorbed on the ground includes the portion of metering delay that was assumed to be incurred on the ground. The total cost of delay for each flight was then calculated by adding the cost of the en-route delay and the cost of the ground delay in each case. The total cost of delay for the reroute under question on the day under question was then calculated by adding the total cost of delay for each flight affected by the reroute, as detailed in the equation below.

$$\textit{Total Cost of Reroute Delay [US\$]} = \sum_{\text{all flts}} \left(\textit{En-route Delay [hr]}_{\textit{flt } i} \times \textit{En-route Op Cost [US\$/hr]}\right) + \left(\textit{Ground Delay [hr]}_{\textit{flt } i} \times \textit{Ground Op Cost [US\$/hr]}\right)$$

The above analysis was completed for each of the cases presented in Section 6. Subtracting the total cost of delay for each alternative from baseline results (applying the FAA specified playbook reroute only, with metering) yields the economic savings of TFM R&D for each reroute.

As described in Section 6, two playbook reroute types were modeled. These were transcontinental playbook reroutes (CAN_1_EAST, VUZ, FAM), and airport closure playbook reroutes (IAH_EAST, DFW_EAST). The average economic benefit of applying SWEPT or FACET-AOC to a playbook reroute can be calculated for each of these playbook reroute types independently, by averaging the savings for each playbook reroute type. These average economic benefits are presented for each of the cases described in Section 6, below.

Improved Rerouting around an FCA using Integrated TFM

The average economic benefits of the selection of an FAA improved reroute for each flight, using an integrated TFM approach, are presented in the tables below for transcontinental playbook reroutes, and airport closure playbook reroutes.

Table 9 shows the average operating cost savings per reroute of using SWEPT and an integrated TFM approach to choose which of two playbook reroutes to implement (case a). The savings are relative to the operating costs of the playbook reroutes actually chosen on each day.

Table 9. Average operating cost savings of FAA selection of reroute 1 or reroute 2

Playbook Reroute Type	# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	Ave. Op. Cost Savings [US$ per reroute]
Transcontinental	3	69	211	**$40,400**
Airport Closure	2	226	503	**$52,800**

Table 10 shows the average operating cost savings per reroute of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and an alternative playbook reroute (case b). The savings are relative to the operating costs of the implementation of the original playbook reroute only.

Table 10. Average operating cost savings of allocation between the original playbook reroute and a playbook reroute alternative.

Playbook Reroute Type	# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	Ave. Op. Cost Savings [US$ per reroute]
Transcontinental	2	52	387	**$57,900**
Airport Closure	2	226	740	**$62,700**

Table 11 shows the average operating cost savings per reroute of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and a customized airline alternative reroute (case c). The savings are relative to the operating costs of the implementation of the original playbook reroute only.

Table 11. Average operating cost savings of allocation between the original playbook reroute and an airline customized alternative reroute.

Playbook Reroute Type	# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	Ave. Op. Cost Savings [US$ per reroute]
Transcontinental	3	69	440	**$57,200**
Airport Closure	2	226	740	**$78,100**

The average transcontinental reroute savings using a customized airline alternative can be seen to be slightly lower than the savings using an alternative playbook reroute, presented in Table 10. This is not expected, as the delay savings presented in Table 4 for the customized airline alternative are slightly higher than the delay savings presented in Table 3 for the alternative playbook reroute. The change in the relationship between the two results is related to the distribution of delay absorbed in the air and on the ground. The cost of delay absorbed in the air is higher than that on the ground. In the airline customized alternative case more of the delay savings were ground delay, and consequently the economic benefit is slightly lower than for the playbook alternative case.

The average airport closure reroute savings using a customized airline alternative can be seen to be higher than the savings using an alternative playbook reroute, presented in Table 10, as expected. This illustrates the benefit of collaboration with the airlines.

Airspace Resectorization

The average economic benefits of using SWEPT to reduce congestion by airspace resectorization are presented in Figure 12 below for no decrease in the resectorized sector capacity, and a 10% decrease in resectorized sector capacity. Airspace resectorization was only simulated for CAN_1_EAST on June 11 2003, VUZ on September 15 2002, and FAM on August 16, 2002. The savings are relative to the operating costs of implementing the playbook reroute, and metering accordingly, without any airspace resectorization.

Table 12. Average operating cost savings of using SWEPT for airspace resectorization.

# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	% Dec. in Resectorized Sector Cap	Ave. Op. Cost Savings [US$ per reroute]
3	69	440	0 %	**$10,600**
			10 %	**$3,500**

Preemptive Airline Collaboration

The average economic benefits of preemptive airline action using FACET-AOC are presented in the tables below for transcontinental and airport closure playbook reroutes. The preemptive action of the airlines includes only refiling flight plans consideration of an integrated TFM approach.

Table 13 shows the average operating cost savings per reroute of preemptive action by a single airline suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute. The savings are relative to the operating costs without any preemptive airline action, and FAA application of only the playbook reroute actually applied on each day.

Table 13. Average operating cost savings for preemptive action by a single airline suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute.

Playbook Reroute Type	# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	Ave. Op. Cost Savings [US$ per reroute]
Transcontinental	3	69	440	**$16,400**
Airport Closure	2	226	740	**$40,500**

Table 14 shows the average operating cost savings per reroute of preemptive action by all airlines suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute. The savings are relative to the operating costs without any preemptive airline action, and FAA application of only the playbook reroute actually applied on each day. These results are identical to those presented in Table 11.

Table 14. Average operating cost savings for preemptive action by all airlines suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute.

Playbook Reroute Type	# Playbook Reroutes Modeled	Ave. # of Flights Rerouted	Ave. # of Flights Metered	Ave. Op. Cost Savings [US$ per reroute]
Transcontinental	3	69	440	**$55,700**
Airport Closure	2	226	740	**$78,100**

It is clear comparing the result in Table 13 and Table 14 that when more airlines operate FACET-AOC, the average savings per reroute over all airlines increases significantly.

7.2. *Extrapolation to Yearly Benefits*

The average economic benefits for each reroute type modeled, presented in Section 7.1, were extrapolated to yearly benefits by identifying the average number of playbook reroutes of each type implemented per year, and extrapolating accordingly. The number of playbook reroutes implemented during the first half of July 2003, and in September 2003, classified according to type, are presented in Table 15 below. July is a summer month, when severe weather is generally more common, and the number of playbook reroutes implemented is thus higher. September represents a month is which severe weather is less common, which is more typical of the rest of the year. The number of playbook reroutes, per month, is correspondingly lower. Note that in the table below fewer days were analyzed in July 2003 than in September 2003. The numbers presented are totals for the periods analyzed, and not monthly averages.

Table 15. Number of playbook reroutes implemented, classified by type.

Period	No. Days	Playbook Reroutes					Other Reroutes
		Transcontinental	Airway Closure	Airport Closure	South to Northeast	Non-Playbook	
July 2 – 15 2003 (excl. July 6)	13	14	5	70	3	10	74
Sept. 2 – Oct. 1 2003	30	24	8	45	3	29	94

Extrapolating the results for July to the whole summer (June to August), and the results for September to the rest of year (September to May), the average number of playbook reroutes of each type implemented per year was estimated. This is as follows:

Transcontinental:	317	reroutes per year
Airway Closure:	108	reroutes per year
Airport Closure:	905	reroutes per year
South to Northeast:	49	reroutes per year
Non-playbook:	335	reroutes per year
Other Reroutes:	1379	reroutes per year

As detailed in Section 6, only two types of reroutes were modeled – transcontinental playbook reroutes (CAN_1_EAST, FAM and VUZ), and airport closure playbook reroutes (DFW_EAST and IAH_EAST). As can be seen above the most commonly implemented reroutes are transcontinental, airport closure, non-playbook and other reroutes. Airway closure and south to northeast playbook reroutes are implemented less frequently.

Airway closure playbook reroutes and south to northeast playbook reroutes are similar in nature to transcontinental reroutes, so the benefits of TFM R&D to these reroutes is likely to be similar to the benefits to transcontinental reroutes. Airway and south to northeast playbook reroutes can thus be assumed to be grouped with transcontinental reroutes, increasing the total number of such reroutes to 474 per year.

Non-playbook reroutes and other reroutes implemented by the FAA differ significantly from transcontinental and airport closure playbook reroutes, as they are more tactical in nature. These reroutes cannot thus be grouped with either transcontinental or airport closure playbook reroutes. Because the benefits of TFM R&D have also not been simulated for such tactical reroutes the benefits of these reroutes cannot be included in the analysis. The results presented below are thus conservative.

The yearly benefits of TFM R&D are calculated accordingly by multiplying the results presented in Section 7.1 for each playbook reroute type by the appropriate average number of playbook reroutes per year presented above. Adding the results for each playbook reroute type yields the total benefits of TFM R&D per year. This calculation is summarized in the equation below:

$$\text{Total Benefit per year} = (\text{Ave. Play Benefit}_{Transcon} \times \text{No. Plays per Year}_{Transcon}) + (\text{Ave. Play Benefit}_{Airport} \times \text{No. Plays per Year}_{Airport})$$

The results of this analysis are presented in the sections below, for each case.

Improved Rerouting around an FCA using Integrated TFM

The yearly economic benefits of the selection of an FAA improved reroute for each flight using an integrated TFM approach are presented in the table below for transcontinental type playbook reroutes (including airway closure and south to northeast playbook reroutes), airport closure playbook reroutes, and the sum of the two. The first result in Table 16 shows the yearly economic savings of using SWEPT and an integrated TFM approach to choose which of two playbook reroutes to implement. The second result in Table 16 shows the yearly economic savings of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and an alternative playbook reroute. The third result in Table 16 shows the yearly economic savings of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and an airline customized alternative reroute. In all cases the savings are relative to the cost of implementation of the reroute actually applied on each day.

Table 16. Yearly economic savings using SWEPT for rerouting around an FCA.

Reroute Alternatives	Playbook Reroute Type	Yearly Savings [US$/year]
Original playbook reroute, or playbook alternative.	Transcontinental[16]	$ 19,160,000
	Airport Closure	$ 47,761,000
	Total	**$ 66,921,000**
Allocation between original playbook reroute, and playbook alternative reroute.	Transcontinental[16]	$ 27,466,000
	Airport Closure	$ 56,787,000
	Total	**$ 84,253,000**
Allocation between original playbook reroute, and airline customized alternative reroute.	Transcontinental[16]	$ 27,118,000
	Airport Closure	$ 70,657,000
	Total	**$ 97,775,000**

The yearly benefits are clearly highest when allocating between the original playbook reroute and either a playbook alternative reroute or an airline customized alternative reroute are applied. This is because the rerouted flights are distributed between two different reroutes, and not on a single reroute as in the case where one of two reroutes is chosen. Capacity is thus increased, increasing the economic benefits over the baseline case in which flights are rerouted on the original playbook reroute only. Airline collaboration, through allocation to a customized reroute, further increases the benefits by $13,522,000 per year over the allocation between playbook reroutes only.

Airspace Resectorization

The yearly economic savings of using SWEPT to reduce congestion by airspace resectorization are presented in Table 17 below, for both no decrease in resectorized sector capacity, and for a 10% decrease in resectorized sector capacity. Airspace resectorization using SWEPT is likely to show similar benefits for any congested sector, which would result from rerouting around an FCA, as in the cases simulated. It is thus assumed that the same benefits identified in the simulations, and presented in Table 12, are applicable to all playbook reroutes that could be implemented in response to an FCA. This includes transcontinental playbook reroutes, airway closure playbook reroutes, airport closure playbook reroutes, and south to northeast playbook reroutes. Again it does not include non-playbook reroutes and other reroutes, as these are likely to be different in nature – i.e. more tactical. The benefits of TFM R&D for sector resectorization have not been simulated for such tactical cases, so these benefits again cannot be included. The

[16] Includes airway closure playbook reroutes and south to northeast playbook reroute.

average savings per reroute presented in Table 12 are thus multiplied by the average number of transcontinental, airway closure, airport closure, and south to northeast playbook reroutes. According to the numbers of each playbook reroute type implemented per year (extrapolated from Table 15 above), this is 1379 reroutes per year. The savings presented in Table 17 below are relative to the cost of implementing the playbook reroute, and metering accordingly, without any airspace resectorization.

Table 17. Yearly economic savings of using SWEPT for airspace resectorization.

Reroute Alternatives	% Dec. in Resectorized Sector Cap.	Yearly Savings [US$/year]
Original playbook reroute, with airspace resectorization	0 %	**$ 14,568,000**
	10 %	**$ 4,763,000**

Preemptive Airline Collaboration

The yearly economic savings of preemptive airline action using FACET-AOC are presented in Table 18 below for transcontinental type playbook reroutes (including airway closure and south to northeast playbook reroutes), airport closure playbook reroutes, and the sum of the two. The first result in Table 18 shows yearly economic savings over all airlines of preemptive action by a single airline suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute. The second result in Table 18 shows the yearly economic savings over all airlines of preemptive action by all airlines suggesting an airline alternative reroute, and allocating between this reroute and the playbook reroute. In both cases the savings are relative to the cost without any preemptive airline action, and FAA application of only the playbook reroute actually applied on each day.

Table 18. Yearly economic savings of preemptive airline action.

Reroute Alternatives	# of Airlines operating FACET-AOC	Playbook Reroute Type	Yearly Savings [US$/year]
Allocation between Airline alternative reroute and original playbook reroute	1	Transcontinental[17]	$ 7,750,000
		Airport Closure	$ 36,616,000
		Total	**$ 44,366,000**
	All	Transcontinental[17]	$ 26,420,000
		Airport Closure	$ 70,657,000
		Total	**$ 97,077,000**

[17] Includes airway closure playbook reroutes and south to northeast playbook reroute.

8. Extrapolation to Future Years

The results presented in Section 7 were extrapolated to future years by modeling increased demand for each of the origin destination markets represented in the analyzed samples. Demand increases relative to 2002 levels are forecast by the FAA APO TAF [10]. Both the baseline and the improvement scenarios were simulated under the increased demand.

Demand was increased by adding flight plans to the simulation input files. Flight plans were added such that the departure rate from each airport is increased to the level predicted by the TAF forecast of each airport [10]. Departures from each airport were added by selecting a flight plan randomly and duplicating it. This maintains the distribution of airlines and flight plans according to the original schedule, since the random process would duplicate the flight plans according to their frequency in the original schedule. The demand was increased in each hour of the day separately to maintain the dynamics of the original schedule over time.

The modeling parameters were not adjusted to reflect any technological improvements. Such adjustments to modeling parameters could include increased sector capacities to reflect improved technologies, addition of runways, navaids, and decision support tools. It was decided that taking such changes into account is beyond the scope of this study.

The results of the extrapolation to 2015 are presented in the tables below. The results presented are yearly economic benefits for transcontinental type playbook reroutes (including airway closure and south to northeast playbook reroutes), airport closure playbook reroutes, and the sum of the two, as presented in Section 7.2. All the results are in 2002 US Dollars. The calculation of yearly benefits is based on the same extrapolation as presented in Section 7.2, including the number of playbook reroutes implemented per year. These numbers are not expected to increase, as the playbook reroutes considered are generally put in place in response to weather, and not traffic volume.

Yearly economic benefits for years other than 2015 can be identified by fitting either a linear or exponential curve to the results for 2002 and 2015, presented in Section 7.2 and below respectively. According to the FAA Terminal Area Forecast [10], NAS wide demand is forecast to increase approximately linearly (R^2 value of 0.9979). According to queuing theory, delay increase exponentially with demand. Delay savings from TFM R&D are expected to be proportional to delay, meaning that TFM R&D economic benefits may increase exponentially with demand. Yearly economic benefits of TFM R&D would thus most correctly be estimated by fitting an exponential curve to the economic results presented in Section 7.2 and below, and the corresponding system wide demand in each case. A linear curve fit would alternatively provide a more conservative estimate of benefits beyond 2015.

Improved rerouting around an FCA using Integrated TFM

The yearly economic benefits in 2015 of the selection of an FAA improved reroute for each flight using an integrated TFM approach are presented in Table 19 below for transcontinental type playbook reroutes (including airway closure and south to northeast playbook reroutes), airport closure playbook reroutes, and the sum of the two. The first result in Table 19 shows the yearly economic savings in 2015 of using SWEPT and an integrated TFM approach to choose which of two playbook reroutes to implement. The second result in Table 19 shows the yearly economic savings in 2015 of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and an alternative playbook reroute. The third result in Table 19 shows the yearly economic savings in 2015 of using SWEPT and an integrated TFM approach to allocate flights between the original playbook reroute and an airline customized alternative reroute. In all cases the savings are relative to the cost of implementation of the playbook reroute actually implemented on each day.

Table 19. Yearly economic savings in 2015 using SWEPT for rerouting around an FCA.

Reroute Alternatives	Playbook Reroute Type	Yearly Savings [US$/year]
Original playbook reroute, or playbook alternative.	Transcontinental[18]	$ 49,837,000
	Airport Closure	$ 116,859,000
	Total	**$ 166,696,000**
Allocation between original playbook reroute, and playbook alternative reroute.	Transcontinental[18]	$ 51,420,000
	Airport Closure	$ 135,533,000
	Total	**$ 186,953,000**
Allocation between original playbook reroute, and airline customized alternative reroute.	Transcontinental[18]	$ 56,747,000
	Airport Closure	$ 193,833,000
	Total	**$ 250,580,000**

Airline collaboration, through allocation to a customized reroute, further increases the benefits by $63,627,000 per year over the allocation between playbook reroutes only.

Airspace Resectorization

The yearly economic savings in 2015 of using SWEPT to reduce congestion by airspace resectorization are presented in Table 20 below for all playbook reroutes. The results are extrapolated to yearly benefits in the same way as presented in Section 7.2, i.e. assuming that the benefits identified in the simulations are applicable to all playbook reroutes that could be implemented in response to an FCA. The savings are relative to the

[18] Includes airway closure playbook reroutes and south to northeast playbook reroute.

cost of implementing the playbook reroute, and metering accordingly, without any airspace resectorization.

Table 20. Yearly economic savings in 2015 of using SWEPT for airspace resectorization.

Reroute Alternatives	% Dec. in Resectorized Sector Cap	Yearly Savings [US$/year]
Original playbook reroute, with airspace resectorization	0 %	**$ 95,561,000**
	10 %	**$ 78,780,000**

Preemptive Airline Collaboration

The yearly economic savings in 2015 of preemptive airline action using FACET-AOC are presented in Table 21 below for transcontinental and airport closure playbook reroutes. The first result in Table 21 shows yearly economic savings in 2015 over all airlines of preemptive action by a single airline suggesting an airline alternative reroute. The second result in Table 21 shows the yearly economic savings in 2015 over all airlines of preemptive action by all airlines suggesting an airline alternative reroute. In both cases the savings are relative to the cost without any preemptive airline action, and FAA application of only the playbook reroute actually applied on that day.

Table 21. Yearly economic savings of preemptive airline action and FAA rerouting.

Reroute Alternatives	# of Airlines operating FACET-AOC	Playbook Reroute Type	Yearly Savings [US$/year]
Allocation between Airline alternative reroute and original playbook reroute	1	Transcontinental[19]	$ 28,497,000
		Airport Closure	$ 129,252,000
		Total	**$ 157,749,000**
	All	Transcontinental[19]	$ 84,143,000
		Airport Closure	$ 193,833,000
		Total	**$ 277,976,000**

[19] Includes airway closure playbook reroutes and south to northeast playbook reroute.

9. Conclusions and Recommendations

The benefit estimates in this analysis are low fidelity and conservative due to a number of reasons listed below. Therefore, they should be considered to be only a portion of the possible total benefits of TFM R&D. Such more accurate benefits should be assessed with more rigor and comprehensiveness in future work as the Technical Readiness Level (TRL) of the TFM R&D tools increase.

1. This study focused on only a subset of the TFM R&D functions. A functional analysis was performed to identify the existing and possible future functions. These functions spanned a wide range and variety that was impossible to encompass within the scope of this preliminary study. Therefore, due to time and resource constraints, only three functions were considered:

    - SWEPT decision support in solving FCA problems
    - SWEPT decision support in airspace design
    - FACET-AOC decision support in airline planning in response to congestion

    Other functional categories that were identified but not analyzed included:

    - SWEPT and FACET-AOC decision support in monitoring system conformance
    - SWEPT and FACET-AOC decision support in evaluation of system performance
    - FACET-AOC decision support at higher level scheduling and market decisions

    Such functions may be analyzed in future research.

2. The three functions selected remained wide in scope as they represented functional categories and still a large number of detailed utilities and scenarios could be listed under each. Due to time and resource limitations again only a subset of these utilities were assessed:

    - SWEPT decision support in rerouting around an FCA in real time
    - SWEPT decision support in airspace resectorization in real time
    - FACET-AOC decision support in rerouting airline flights around an FCA preemptively

    Other utilities that were identified under these functional categories but not analyzed included:

    - SWEPT decision support in temporal restrictions such as Miles In Trail and Ground Delay
    - SWEPT decision support in offline airspace redesign
    - FACET-AOC decision support in real time departure time change and cancellation

    Such additional utilities may be analyzed in future research.

3. The benefit mechanisms of these three functions or utilities were identified and represented in charts. However, time did not permit to analyze and assess the benefits of all mechanisms, as each mechanism needed more scenarios to be generated and simulated. The benefit mechanisms that were analyzed included:
    - The use of SWEPT for simulating different playbook reroutes and selecting one reroute based on integrated rerouting and metering – only one example of possible integration between TFM programs. The reroute with least total delays was selected where total delays were caused by reroute distance and metering due to congestion
    - The use of SWEPT for allocating and distributing flights over more than one reroute, also integrating rerouting and metering in the allocation decision
    - The use of SWEPT for collaboration with airlines to allocate flights between playbook and customized reroutes
    - The use of SWEPT for changing sector boundaries to reduce sector overload and reduce the need for metering
    - The use of FACET-AOC for one airline or all airlines re-filing of alternate routes for their flights affected by an FCA to reduce the need for FAA metering

    In the above rerouting scenarios were selected to cover the two most prominent playbook reroute types: airport closures and transcontinental reroutes. While these are the two dominant reroute types, others may also be analyzed in future work.

    Other benefit mechanisms of the specific utilities (rerouting and resectorization) analyzed that were identified in this study but not analyzed, include:

    - Selection of different set of flights to reroute
    - Selection of different reroute timing and duration
    - Accounting for FCA uncertainty
    - Resectorization effects other than metering reduction
    - Other effects of airline preemptive actions such as excluding the need for an FAA action altogether as opposed to keeping the same action but reducing its effect as the scenario in this study assumed

    Such additional benefit mechanisms may be analyzed further in future research. Also other benefit mechanisms and corresponding scenarios that were not identified in this study may be further investigated and assessed in future research.

In addition a number of simplifying assumptions were made in this study, which were deemed appropriate given the wide scope of functions covered and the non-constraining fidelity requirements. Therefore, a number of recommendations can be made in order to refine the current models and analyses and increase the level of fidelity in future research:

1. In this study metering was modeled outside FACET using a simple time-slot allocation algorithm. Metering was performed at only the most congested sector along a reroute. The metering model may be improved to include metering at all congested sectors along a reroute and the propagation of delays between them. Such a model may require programming inside FACET (which contains the sector connectivity structure), which was avoided in this study due to time limitations.
2. Increasing the number of scenarios and examples in order to improve the statistical significance of the results (it was only possible to analyze five rerouting examples in this study).
3. Improving the airline model for reroute selection, for example, using a model that selects a different reroute for each airline based on their route/hub structure and their on-time performance objectives. Building such a complex model was beyond the scope of this preliminary study.
4. The baseline for the airspace resectorization scenarios in this study assumed that the FAA performs no resectorization currently. More research is needed to determine the current level and quality of airspace resectorization behavior and model it as a baseline.
5. Dividing the saved minutes of delay between ground and air was based on a simple model: the historical breakdown of air/ground delay. The fidelity of this model may be improved in future research, which may require detailed modeling of ground holding behavior and procedures (which were not covered in this study).
6. Allocation of flights between two reroutes used a simple algorithm that allocates flights between the two most congested sectors on each reroute. More sophisticated reroute allocation algorithms may be developed in future research, that allocate flights among a larger number of reroutes and sectors.
7. Also there is great potential to develop more variety and complex scenarios and algorithms for integrating rerouting and temporal restriction in future research. Only one example of such integration was analyzed in this study.

The lists above indicate that significant number of more functions and benefit mechanisms of the TFM R&D tools may be analyzed and their benefits assessed than was performed in this study. This leads to the belief that the benefit estimates reported in this study are conservative, both for TFM R&D in general and for the specific functions analyzed in particular. This study covered more functions at the expense of more details and coverage for each specific function. Future work may focus on each individual function and perform more comprehensive and higher fidelity assessment of its benefits. This study can serve as a starting point and a preliminary assessment.

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